Panta Rhei benchmark dataset: socio-hydrological data of paired events of floods and droughts – Paired event reports*

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ID 1

Paired pluvial flood events: 21st July 2012 and 20th July 2016 pluvial floods in the city of Beijing, China

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Short description of both events with a focus on impacts

The 21st July 2012 and 20th July 2016 storms are two representative cases of extreme flood-producing storms in the city of Beijing, China. The two storms are comparable in storm intensity, duration and spatial coverage. Both storms set historical rainfall records in Beijing. The maximum rainfall accumulations (i.e., at point scale) for the 2012 and 2016 storms are 372 mm and 381 mm, respectively, with the return intervals of approximately 60-80 years. Extreme rainfall and flooding caused severe damages in many societal and economic sectors (e.g., agriculture, transportation, aviation, etc.). The 2012 storm is the deadliest and costliest weather disaster in Beijing since 1951, with 79 fatalities, economic loss of up to 16 billion RMB, loss of crops for 67,000 hectares, cancellation of more than 500 flights (Sun et al., 2012; Guo et al., 2015). The 2016 storm, on the other hand, did not induce as severe damages/losses as its counterpart. For instance, there were 380 flights cancelled during the 2016 storm event, loss of crops for 2,140 hectares, economic loss of less than 3 billion RMB. No fatalities were reported for the 2016 storm.

Descriptions of processes between events with a focus on risk management

The Beijing government implements several practices for flood mitigation/adaptation after the 2012 storm. Zhang et al. (2017) provided a list of the practices: (1) capacities of drainage systems are increased, especially for the areas where water-logging is common; (2) urban channels with a total length of 1460 km are cleaned up and connected to adjacent lakes/ponds; (3) 75 pumping stations are re-built through increasing drainage capacities to prevent ten-year flood events; (4) Additional 47 flood detention sites are set up in Beijing. These engineering measures effectively control inundation and its damages to societal and economic sectors during the 2016 storm. In addition, the Chinese government started great investments for flood prevention and mitigation in urban areas since 2013, the so-called “sponge-city” initiative, which increases institutional awareness for urban flooding over the entire country and promotes a favorable environment for collaborative efforts among different agencies.

Event comparison in respect to pluvial flood hazard

The 2012 and 2016 storms are comparable in storm intensity, duration and spatial extent. The storm-total rainfall accumulation averaged over the entire city is 213 mm (215 mm) for the 2012 (2016) storm. The maximum hourly rainfall is 100 mm/h for the 2012 storm, slightly larger than that of the 2016 storm (57 mm/h). Both storms persist for more than 20 hours, with the 2016 storm continuing for approximately 40 hours. Despite the comparable statistics, the synoptic conditions for the two storms are dramatically different from each other. The 2012 storm is associated with the deepening westerly trough (i.e., cold vortex) and its southward propagation. Interactions of the cold vortex and subtropical high promotes strong convergence and uplifting in northern China (Sun et al., 2012; Guo et al., 2015). An additional feature for the 2012 storm is the contribution of southwest low-level jet that brings moist and unstable air plumes into the storm which maintains moisture supply and uplifting for the storm for more than 20 hours. Low-level convergence combined with upper-level divergence leads to strong convection and outbreaks of thunder. The 2016 storm is associated with northward propagation of so-called "Yangtze-Hui cyclone". The cyclone is initiated in the lower Yangtze River and Huai River due to the convergence of the Indian monsoon and East Asia summer monsoon. The outbreak of convection is related to the cold air plume running down from the north. From the perspective of large-scale pattern, the propagation of the Yangtze-Huai cyclone is promoted by the northwestward extension of West Pacific Subtropical High. The blocking high in the West slows down the propagation and enables the storm to maintain for more than 40 hours (Kang et al., 2019). The 2016 storm characterized with a "low-echo top" cloud structure, and is relatively "mild" in terms of convective activities in comparison to the 2012 storm.

Event comparison in respect to exposure

no significant contrasts in exposure are identified between the two events. As can be seen from Figure 1, the spatial distributions of rainfall accumulation for the two cases are comparable. Both storms center over downtown Beijing, even though the 2016 storm exhibits relatively larger rainfall totals than the 2012 storm. We do not find remarkable changes in terms of population densities and lay-out of economic assets between the year 2012 and 2016.

Event comparison in respect to vulnerability

One of the great legacies for the 2012 storm is the reforms of flood warning and management agencies in Beijing, among which, the establishment of flood emergency management center is the most prominent one (Zhang et al., 2017). The mayor of Beijing takes full responsibilities for the organization of the flood emergency management center which consists of persons in charge from key societal sectors, including water conservation, civil, transportation, environment protection and health. The leadership of mayor and the accompany of key persons in change facilitate full utilization of existing resources for effective mitigation and adaptation strategies in Beijing. These measures significantly improve flood preparedness and emergency management for the 2016 storm in comparison to the 2012 storm.

Summary

Awareness comes the first. The 2012 storm, to some extent, rings the alarm and forces immediate measures to be implemented. The Beijing government and other associated agencies set an excellent example for urban flood prevention and mitigation for other cities in China. The coping abilities for flood hazards can be further enhanced through combinations of engineering and non-engineering practices, such as early warning system. Better city designs can help alleviate exposure and vulnerabilities to urban flooding for mega cities, like Beijing.

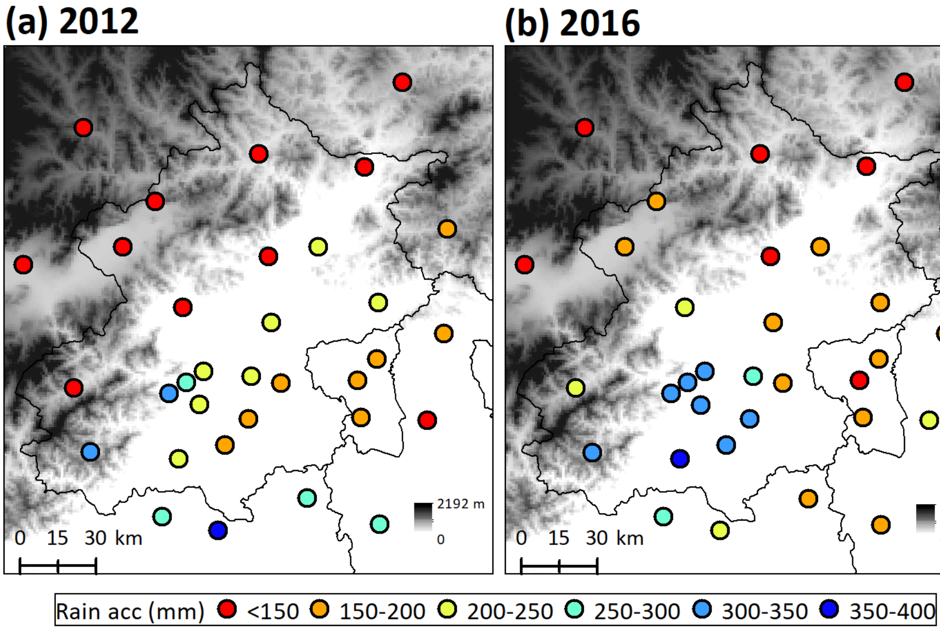

Figure 1. Rainfall accumulation (scatter, in mm) for the (a) 21st July 2012 and (b) 20th July 2016 storm. Black lines show the administrative boundary of Beijing.

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ID 2

Paired riverine flood events: The 1951 and 1993 riverine flooding events in the Kansas River System

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Short description of both events with a focus on impacts

The Kansas river system flood events of 13 July 1951, and 27 July 1993, are part of the widespread flood events known as "The Great Flood of 1951" and "The Great Flood of 1993" occurred in the Mississippi and Missouri river systems (Lott, 1993), respectively. The 1951 flood event was mostly confined to the Kansas River system (USGS, 1952; Veatch, 1952). It resulted in a loss of 28 lives, displacement of more than 518,000 people, and caused damage of more than \$725 million (~\$7.03 billion in 2019 currency) (USGS, 1952). Agricultural damage in the Kansas River Basin is estimated at over \$93 million (~\$923 million in 2019 currency) (Cox et al., 1981), with about 900,000 acres flooded (Veatch, 1952). Damage to municipal water supplies and sewage treatment works was also extensive. About 1100 people were injured, and in Kansas, 33 water-supply systems were shut down (Juracek et al., 2001). The 1993 flood spreads over the Midwest US in general. It caused a loss of 50 lives, failure in hundreds of levees, destroyed more than 10,000 homes, nearly 75 towns were completely under floodwaters, and at least 15 million acres of farmland were inundated (Brown et al., 1994). The total damage was estimated to be ~\$15 billion at the time (~\$26.69 Billion in 2019 currency) (Combs & Perry, 2003). Though moderate to major flooding occurred in large part of the Kansas River basin during the July-1993 flood, only unprotected areas in the tributaries were inundated. However, no lives were lost, and property damage was substantially lower (Perry et al., 1997). Kansas state's total damage was estimated at a little more than \$551 million (~\$954.13 million in 2019 currency), of which \$441 million (~\$765.71 million in 2019 currency) is an agricultural loss (Interagency Floodplain Management Task Force (IFMTF), 1994).

Descriptions of processes between events with a focus on risk management

The magnitudes of the 1951 and 1993 floods at De Soto, KS were 13,762 m^3/s and 4785 m^3/s, respectively. However, prior to 1951, the levees and floodwall systems along the banks of Kansas River, even for cities downstream of Topeka, including Argentine, Armour dale, and Kansas City, were designed for a maximum flood of 7362 m^3/s (USGS, 1952; Veatch, 1952). As such, the levees and floodwall systems were overtopped at all points along the riverbank (Veatch, 1952). Before 1951, only five major flood control reservoirs with a total capacity of 1 billion cubic meters were regulating the Kansas River system (Perry, 1994). Following the 1951 flood, several flood control reservoirs with a total volume of 1.5 billion cubic meters were proposed (Veatch, 1952). By 1993, 85% of the river basin area is regulated, and the number of reservoirs has been increased to 18, with a total storage capacity of 9.12 billion cubic meters (Perry, 1994). About 35 % of the flood magnitude observed at Topeka was contributed from the Big Blue River basin, which drains ~ 16% of the Kansas River basin. During the 1993 flood, the Tuttle Creek Lake, a flood control reservoir constructed on the Big Blue River in 1962 following the 1951 disasters, could not accommodate the incoming flood (Combs & Perry, 2003). Reports indicated that on 23 July 1993, the lake was at about 20m above its normal pool level. The reservoir's length increased from ~ 25 km to 80 km. The surface area increased from ~56.7 to 218.5 km^2 (Combs & Perry, 2003). As such, the integrity of the dam was threatened and forced the Army Corps of Engineers to fully open all 18 spillway gates, which resulted in the increase of reservoirs release from about 283 m^3/s to nearly 1926 m^3/s (Miller, 1994), which then caused large-scale erosion in the spillway channel. Based on a back-casting LULC data developed by Sohl et al. (2016), a comparison of 1951 and 1992 LULC maps for the Kansas river basin shows an increase in an open water area (by ~ 380 km^2), developed area (~460 km^2) and agricultural land (by ~6450 km^2).

Event comparison in respect to riverine flood hazard

Data analysis indicated that the drivers of both 13 July 1951, and 27 July 1993, flood events were the combined effects of a series of rainfall events and antecedent soil moisture. The cumulative rainfall and antecedent soil moisture in both cases were above the 5% exceedance of the analyzed 81 years of data (1930-2010). The basin average cumulative rainfall leading up to the flooding day was found to be five days cumulative for 1951 and ten days for 1993; the corresponding total basin average rainfall magnitudes were ~98 mm and ~115 mm, respectively (Fig. 1). The soil moisture excess (Berghuijs et al., 2019) during the days leading to both flood events occurrences was also far below the 5% exceedance. Though the magnitude of the 1951 cumulative rainfall event is less than the 1993 occurrence and the flooded area is relatively the same (FEMA, 2003; USGS, 1952), the resulting flood of 1951 is substantially more significant than the 1993 flood. This may be attributed to the dumping effect exerted by the major flood control reservoirs and levees developed following the 1951 disaster. For instance, even though the accumulated rainfall magnitude for the Blue River catchment were ~95mm and ~150mm over 5-days (1951) and 9-days (1993) respectively, at Manhattan, the Big Blue River was discharging at a rate of 1684.85 m^3/s during the July-1993 flood, which is substantially less than the 1951 flood (2446.57 m^3/s).

Event comparison in respect to exposure

During the July-1951 flood event in the Kansas River Basin about 7, 000 people were evacuated from farm homes. In towns and cities, 22,370 residences and 3265 business establishments were flooded, of which 2480 residences and 336 businesses were destroyed (Kansas Historical Society, 2011). The cities along the Kansas River system were substantially affected. For instance, Manhattan, Topeka, and Lawrence suffered severe damage. In Topeka city alone, about 7,000 homes and 530 business establishments were inundated up to 15ft, and over 24,000 people were evacuated (The Kansas Department of Agriculture, 2019). In the Manhattan area, the business district was covered with about 8ft of water (Kansas Historical Society, 2011). In contrast, in July 1993, no life was lost in Kansas (Combs & Perry, 2003). The flood was 9ft above flood stage near Topeka. However, the levees system withstood higher water levels and limited the severity, and only minor damages were reported (Perry, 1994; United States General Accounting Office, 1995)). In Manhattan, the Tuttle creek reservoir was discharging at approximately 1926 m^3/s; simultaneously, the Kansas River at Big Blue River confluence was peaking. The simultaneous occurrence forced the Big Blue River to encroach near topping the levee systems in the Manhattan area, flooding residences, and businesses. The resulting damage was estimated at $1.4 million (~2.49 million in 2019 currency). Similarly, in Lawrence, the local system of levees and reservoirs protected the city, and only about $1.2 million (~$2.14 million in 2019 currency) in damage was reported at the time; most of the damage was from unprotected areas.

Event comparison in respect to vulnerability

Although the river forecast centers, including the Missouri Basin River Forecast Centre, were established in 1946, their capability during 1951 is very limited compared to early 1990s. These can be attributed to the increasing computational capabilities of the river forecast centers, e.g., the gateway computer system was established in 1981, and significant advances in hydrologic model developments in the 1960s and 1970s. Both have substantially improved the forecasting techniques prior to the 1993 flood. Also, the US government did not establish a method to broadcast warnings to the citizens until 1963. In terms of coping capacity, before 1951, flood insurance was not available. On 1 August 1968, Congress established the national flood insurance program in enacting the Housing and Urban Development Act of 1968. Still, the program was strictly voluntary based at the time, and the purchase of insurance coverage was not mandatory for any individual or localities. Thus, in 1973 the Congress amended the 1968 act to strengthen local participation incentives, followed by the Flood Disaster Protection Act of 1973. In June 1978, President Carter established the Federal Emergency Management Agency (FEMA) as an independent agency within the Executive Branch to coordinate federal hazard mitigation efforts. Local and federal governments' coping and recovery capacity during 1993 was better than in 1951. Prior to the 1993 flood, only 10 - 20 percent of insurable buildings in the identified flood hazard areas are covered by flood insurance; the nationwide range was 20-30 percent (Galloway, 1995). The flood insurance market penetration regarding the general 1993 flood area ranges from less than 10 percent in small rural communities to 50 percent for communities with a high level of flood awareness, and for most medium to large communities, in the 20 to 30 percent range. The effect of the 1993 flood on public perception has resulted in an increase in flood insurance coverage by 115 – 150 percent by 2003. The total coverage in 2003 is $1 Billion (FEMA, 2003). The federal crop insurance participation for Kansas State is also ~76% (IFMTF, 1994).

Summary

Compared to the July-1951 flood, the cumulative rainfall and soil moisture excess responsible for the July-1993 flood event was significantly higher. However, the resulting flood discharge magnitude at cities on the river systems' main stems, including Manhattan, De Soto, and Topeka, was less than 50% of the July-1951 flood event. This is primarily attributed to the flood-control reservoir and levees system in the Kansas River basin; for instance, due to upstream reservoirs and levees, ~5.6 billion (~9.7 billion in 2019 currency) damage is prevented in Kansas City (Perry, 1994). Besides, the date of occurrence in major flood contributing sub-basins like Big Blue River was similar during the July-1951 event, but for July-1993 flood delays of 3-day and 4-day was observed between Manhattan and Topeka, and Manhattan and De Soto, respectively. The damage caused by the July-1993 flood was substantially lower. This can be attributed to the increase in flood control reservoirs by nine folds and protective levees. No life was lost in the Kansas River basin, and the property damage was far below that during the 1951 flooding disaster. The main reasons also include the increased flood awareness, the federal governments' attention towards improved forecast systems, and warning broadcasting systems developed between 1951 and 1993.

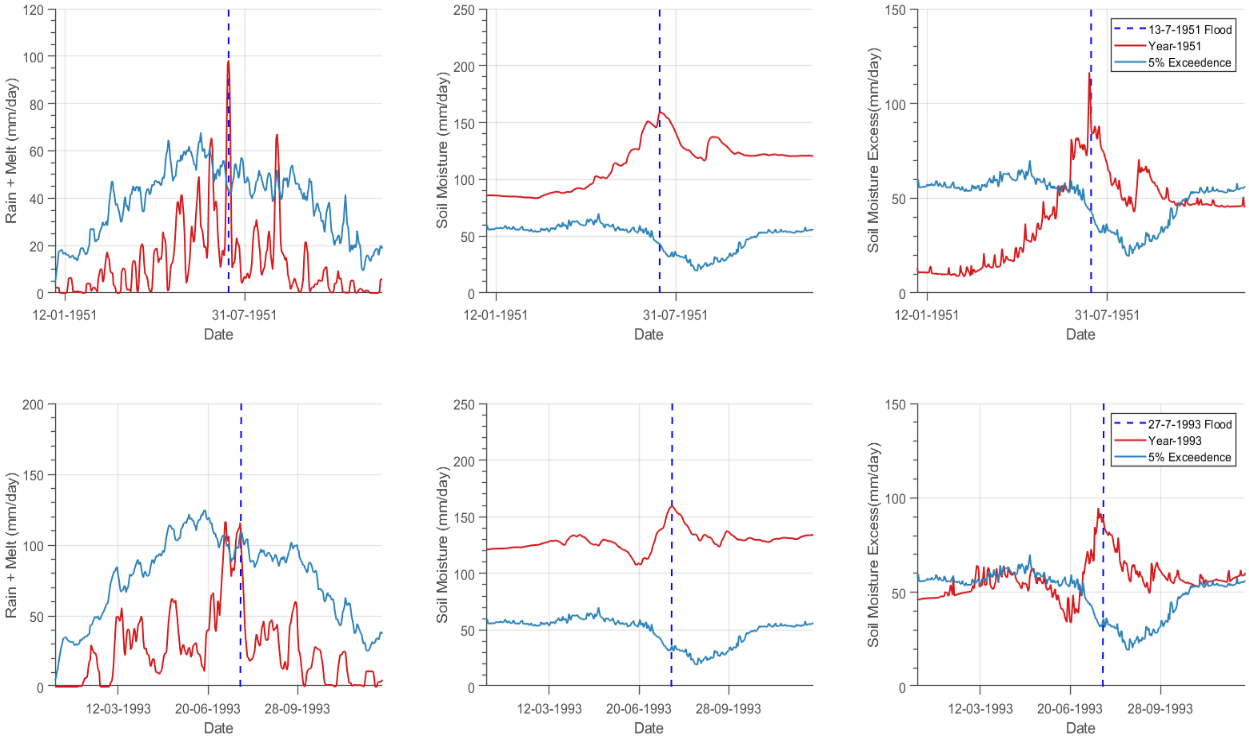

Figure 1: The 13 July 1951 and 27 July 1993 flood generation mechanisms for Kansas River at DeSoto: The rain + melt values are 5-day accumulation for the 1951 flood and 10-day accumulation for the 1993 flood. The 5% exceedance rain + melt, soil moisture, and soil moisture excess were computed for each day separately using 81 years of data (1930-2010, Livneh et al., (2015)). The soil moisture excess was computed following the method presented in Berghuijs et al. (2019).

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ID 3

Paired riverine flood events: The 1963 and 1996 riverine floods in the Baiyangdian catchment in China

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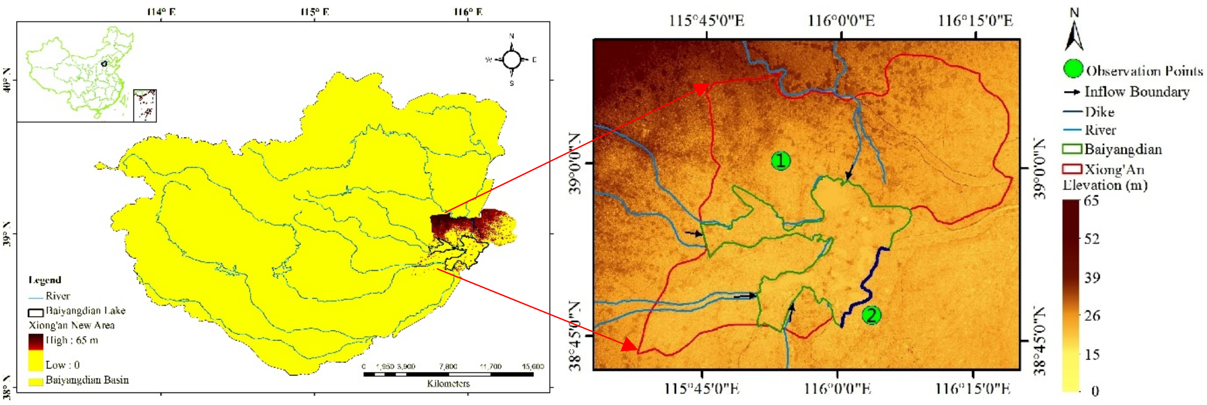
Study area: the Baiyangdian catchment in China

Baiyangdian (BYD) catchment lies in the middle stream of Daqing River catchment within Haihe River basin, with about 108 km south of Beijing. The Xiong'an New Area to be created in plan, which includes the counties of Xiongxian, Rongcheng and Anxin of Hebei Province, is situated in this region (see Figure 1). As a major historic strategic choice made by President Xi, the establishment of Xiong'an New Area is the national event of the millennium. Xiong'an New Area will cover about 2,000 km^2 with a population of 2 to 2.5 million and be planned and constructed as President Xi's call "world vision, international standards, Chinese characteristics and high goals". More information of Xiong'an New Area can be found by this link http://english.xiongan.gov.cn/index.htm.



(a) (b)

Figure 1. Baiyangdian catchment (a) and Baiyangdian lake and Xiong'An area (b) [1]

The BYD Lake is the largest freshwater lake and wetland in North China Plain, with a total surface area of 366 km^2. As shown in Figure 1(b), observation points are presented as green point with the number in the center; the BYD Lake is the area surrounded by the green line; the Xiong'an New Area is surrounded by the red line; the light blue lines stand for the rivers; the dark blue line is the dike. The black arrow denotes the location and direction of inflow. The lake depth varies by hydrologic conditions, but is usually less than 2.0 m [10]. In this region, the annual mean temperature generally falls into the range of 7-12 °C, and the annual mean precipitation is around 550 mm. Due to the dominance of continental monsoon climate, the hydro-climatic regime of this region is characterized with clear wet and dry seasons within a year. The cumulative precipitation in July-September contributes 80% of annual total precipitation. This unevenly distribution of annual and inter-annual precipitation makes it susceptible to flood risk [10].

Short description of both events with a focus on impacts

In August 1963, the BYD region was hit by an ever-recorded extreme storm with 7-day (August 3-9) consecutive areal precipitation over 400 mm, resulting in an unprecedented disastrous flood. During the period of 1963-8 flood, the BYD Lake received about 6 billion m^3 upstream water and the water level exceeds 11 meters for 13 days, causing huge losses in economy and human livelihoods [3].

In August 1996, under the influence of No. 8 typhoon and cold air, the Haihe river basin was hit by heavy rain from August 2 to 6. The observed discharge into BYD lake from August 5-7 is shown in Figure 1 [21].

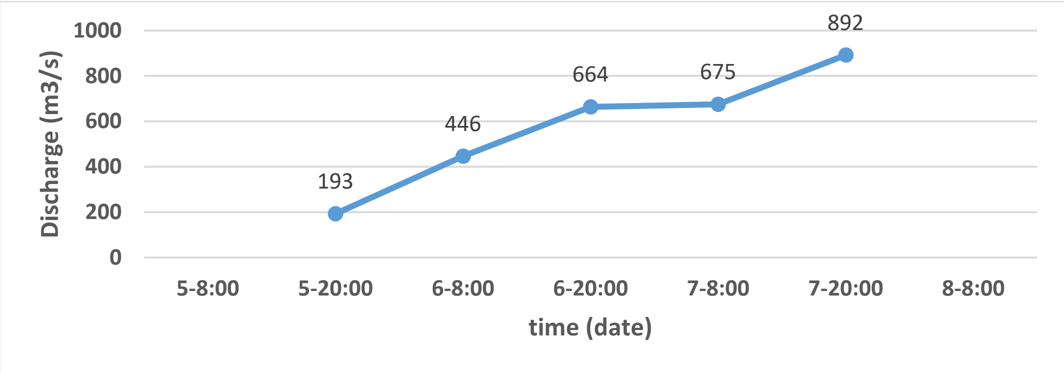


Figure 1 The observed discharge into BYD lake from August 5-7.

The 1963 riverine flood event: In the south branch of BYD basin, the average rainfall is 595mm, the runoff depth is 286mm, and the total runoff volume is 5.995 billion m^3. In the north Branch of BYD basin, the average rainfall is 410mm, the runoff depth is 154mm, and the total runoff volume is 1.539 billion m^3. 1963: In BYD basin, the flood caused 1934 km^2 crop field inundated, more than 180000 houses collapsed, 1.2 million people affected, more than 500 people killed; more than 5000 livestock died.

The 1996 riverine flood event: The flood affected 320,000 people around BYD lake and downstream areas, flooded more than 400 km^2 of farmland and reed fields, affected 1,700 enterprises in the town and village, destroyed more than 100,000 houses, and damaged more than 600 km rural roads. Infrastructures such as broadcasting, communication and electricity facilities were severely damaged, with direct economic losses of 5 billion yuan (in BYD basin).

According to the available data, the real purchasing power 100 RMB in 1978 is about 400 RMB in 1996 and 639.12 RMB in 2018. We cannot get the CPI data before 1978. In addition, the statistical data present some discrepancy due to different scales.

Descriptions of processes between events with a focus on risk management

The structural strategy in Haihe River basin was operated since 1986 [19]. In this context, compared with the 1963 flood event, ability and initiative to prevent flooding disasters were greatly improved in the 1996 flood event. However, the socio-economic outlook in 1996 were greatly changed than that in 1963. Although the water conservancy projects played a key role in reducing disaster losses to a great extent, economic losses were still largely increased due to the increase in population density and economic development. Besides the natural drivers of climate and topography, the artificial drivers also exacerbated the consequences of the floods. The artificial drivers may include 1) the occupation of river channel for farming and building houses; 2) low coverage rate of forest vegetation; 3) lack of flood risk consciousness; 4) low level of flood forecasting techniques.

Event comparison in respect to riverine flood hazard

In August 1963, the BYD region was hit by an ever-recorded extreme storm with 7-day (August 3-9) consecutive areal precipitation over 500 mm, resulting in an unprecedented disastrous flood (referenced as 63.8 flood). During the period of the August 1963 flood, the BYD Lake received about 6 billion m^3 upstream water and the water level exceeded 11 meters for 13 days, causing huge losses in economy and human livelihoods [3]. The highest water level was 11.58m in the Shifangyuan station in Baiyangdian Lake on 14th August, and the corresponding volume was 4.172 billion m^3. The water level start to drop down slowly since 15th August, and drop to below 11m on 19th August [2].

In August 1996, a severe storm rain hit the BYD region within 3 days (August 3-5) leading to an extreme flood disaster [20]. Compared with the August 1963 flood, the peak flow is larger and the duration is relatively shorter [20]. During the period of the August 1996 flood, the BYD Lake received about 1.536 billion m^3 upstream water and released about 1.335 billion m^3 to the downstream, causing direct economic losses nearly 5 billion RMB [2]. On August 1st, the water level of Shifangyuan station in Baiyangdian Lake was 8.34m, and the corresponding storage capacity was 324 million m^3. On August 14, the water level of Shifangyuan was 9.08m. On August 16, the highest water level of Shifangyuan was 9.15m [2].

Event comparison in respect to exposure and vulnerability

(1) 1963 flood event

The range of rainfall is stable, lasting for a long time, with high intensity and wide range of heavy rain. The entire rainfall process was from August 1 to 10. From August 3 to 8, the upper reaches of the Daqing River were covered in the range of heavy rain. The upstream mountainous region with rainfall more than 1000mm is about 840 km^2. The total precipitation in the Daqing River basin was 18.547 billion m^3, with an average rainfall of 463 mm. The maximum 7-day rainfall is 1329mm at Qiyu station. The above records are ref to [13].

The storage capacity of medium-sized reservoir is greater than or equal to 10 million m^3 but less than 100 million m^3. The storage capacity of small (I) reservoir is greater than or equal to 1 million m^3 but less than 10 million m^3. The storage capacity of small (II) reservoir is greater than or equal to 0.1 million m^3 but less than 1 million m^3. There are 906 small and medium-sized reservoirs in Haihe River basin. There are 75 medium and small (I) reservoirs with a storage capacity of more than 1 million m^3. There are 831 small (II) reservoirs with a storage capacity of less than 1 million m^3. The statistics analysis is carried out based on the small and medium-sized reservoirs with a storage capacity of more than 1 million m^3. The total controlled watershed area is 3,054 km^2, with a total storage capacity of 623 million m^3. In 1963 flood event, a total of 380 million m^3 of flood water was blocked by these reservoirs. The above records are ref to [12].

The upstream reservoir played a key role in blocking the flood and cutting the peak, and the downstream low-lying lakes held the flood. In August, the large and medium-sized reservoirs and low-lying lakes blocked and stored 14.133 billion m^3. In order to reduce the burden of downstream flood control engineering, flood diversion measures were adopted in many upstream river sections. However, due to the large flood peak, the losses are still very serious. The flood disaster hit 7 special districts and 101 counties/cities. There are 2,257 enterprises in Baoding, Xingtai, Handan, Shijiazhuang, Xingtai and Baoding cities that stopped production. 822 locations of Beijing-Guangzhou, Shi-De and Shi-Tai railways were destroyed by flood, with a total length of 116.4km. The Beijing-Guangzhou railways was cut off for 27 days. Road traffic in seven regions was almost completely disrupted. The water conservancy projects were also seriously damaged, with 330 small reservoirs, 4 medium-sized reservoirs damaged due to overtopping. There are 2,400 major river channel and 4489 tributary burst their banks. In total, more than 20,000 villages were affected by the flood, with 12.65 million houses collapsed, 22 million people affected and 5,300 people killed, 4.4 million hectares of farmland flooded, 3 billion tons of grain cut, and 6 billion yuan of direct economic losses incurred. The above records are ref to [19].

Flood emergency operation: 1) Strengthen the leadership of flood-control work, strictly implement the leadership responsibility system; 2) Organize the flood control team in advance, and ask the people's liberation army (PLA) for support if necessary; 3) Prepare communication and lighting equipment, and other necessary flood-control materials; 4) On-site command and control.

(2) 1996 flood event

The range of rainfall is large, lasting for a long time, with short-term high intensity. The entire rainfall process lasted from August 2 to August 5. The upper reaches of the Daqing River were in the range of heavy rain. During the whole rainfall process, the total amount of precipitation in the Daqing River basin was 6.201 billion m^3, with an average rainfall of 154.8 mm. The maximum 3-day rainfall was 312 mm at the Angezhuang reservoir. The above records are ref to [13].

There are 91 cities including 15,000 villages were affected. Some mountainous areas were severely impacted by landslides and mudslides. After the flood reached the plain, a large number of farmlands and villages, located in flood detention area, were inundated, with 1,336 industrial and mining enterprises and 94,000 township enterprises affected. 15 national highways and 76 provincial highways were damaged to varying degrees. 396 bridges, 2764 culverts, 6250 km of road subgrades, 5.7 million meters of communication lines, and 7.963 million meters of transmission lines were destroyed. Water conservancy facilities for farmland were seriously damaged. In the Hebei province, 74 large and medium-sized irrigation fields were damaged, directly affecting 266,400 hectares of irrigation fields, 11 large reservoirs, 21 medium-sized reservoirs, 200 small reservoirs. 86,000 hectares of cultivated land were destroyed, 370 million tons of grain and 100 million kg of seeds were damaged, 42,000 hectares of timber forest and 238,300 hectares of economic forest were damaged, and 169,000 big farm animals died in this disaster. 7,670 primary and secondary schools in rural areas were hit by this flooding disaster, with 391 school destroyed. A total of 2.03 million houses collapsed and damaged in Hebei province, with 151,700 people affected, 671 dead and 45.63 billion yuan of direct economic loss. The above records are ref to [19].

Flood risk management [16]: 1) Tracking the trend of typhoons and carrying out "risk prediction"; 2) Repeatedly monitoring and carrying out "risk assessment"; 3) Operating emergency measures and carrying out "risk treatment", including: operating emergency deployment to deal with flood risk; implementing scientific dispatching to control flood risk; making scientific decisions to withstand flood risk; transferring people in time to avoid flood risk.

Flood emergency managing mechanisms [16]: 1) Building flood-control engineering system to improve flood control and security capability; 2) Building organization and command system to improve risk decision-making capability; 3) Building scientific dispatching system to improve flood management capability; 4) Building laws and regulations system to improve flood-control capability; 5) Building social security system to improve capability of flood control and disaster reduction.

Summary

Although the 1996 flood return period (8-year) [6] is much smaller than the one of the 1963 flood (50-year) [2], the disaster loss is much larger than the damage of the 1963 flood [2]. The establishment of the Xiong'an New Area has greatly increased the importance of the BYD region. In order to ensure the socio-economic development and people's life and property safety, to reduce flood damage, it is imperative to develop scientific flood control engineering system and flood risk management under the influence of climate change and urbanization.

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ID 4

Paired riverine flood events: 2002, 2007, and 2013 riverine floods in Jakarta, Indonesia

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Short description of events with a focus on impacts

The city of Jakarta is at the lowest end of the river catchments of greater Jakarta. The longest river, the Ciliwung, stretches 119km from Mount Pangrango (3,019m) to the bay of Jakarta. The flood events of 2002 (peak on 1 February 2002), 2007 (peak on 1 February 2007), and 2013 (peak on 16 January 2013) in Jakarta are the most devastating riverine floods in the city's history. The floods in 2002 and 2007 are estimated to have had a return period of 50 years (Bappenas, 2010), with the 2013 flood having a return period of 30 years (Budiyono et al., 2016). Jakarta's return period calculation is based on a gauge at Bureau of Meteorology office.

The floods caused direct mortalities of 80 in 2002 (Bappenas, 2007), 79 in 2007 (Bappenas, 2007), and 38 in 2013 (BPBD, 2013). The events led to the displacement of 154,270 people in 2003 (BNPB, 2017), 590,407 in 2007 (Bappenas, 2007), and 87,291 people in 2013 (Evan, 2015).

Direct damages of the flood events[a] are estimated at USD 3,092 million for 2002 (Bappenas, 2007), USD 1,859 million for 2007 (Bappenas, 2007), and USD 1,015 million for 2013 (Lurah Galur et al., 2013; Lurah Karet Tengsin et al., 2013; Lurah Petamburan et al., 2013). Table 1 shows impacts to buildings in detail, as published by both BNPB (2017) and Bappenas (2007).

Indirect damages of the flood events are estimated at USD 2,577 million for 2002 (Bappenas, 2007), USD 1,287 million for 2007 (Bappenas, 2007), and USD 130 million for 2013 (Lurah Galur et al., 2013; Lurah Karet Tengsin et al., 2013; Lurah Petamburan et al., 2013).

[a] *All values in USD 2018 values. Original values in Rupiah (IDR) for year of event were converted into USD values for year of the event using exchange rates from the World Bank (https://datacatalog.worldbank.org/dataset/world-development-indicators), and then adjusted to 2018 values using GDP deflators (https://data.worldbank.org/indicator/NY.GDP.MKTP.CD)*

Table 1. Impacts to buildings recorded by BNPB (2017) (first value) and Bappenas (2007) (second value)

Year	Destroyed house	Medium destroyed house	Lightly destroyed house	Destroyed worship place	Destroyed education place
2002	0/na	na/na	0/na	0/na	0/na
2007	7,083/8,977	na/13,466	17,874/67,328	498/na	4/na
2013	3/na	na/na	952/na	0/na	0/na

Descriptions of processes between events with a focus on risk management

In terms of regulations, information, and knowledge building, there has been a lot of change between flood management before and after the flood of 2007. Up to Jakarta's flood event in 2007, disaster management was the responsibility of a committee amended by Presidential Decree No. 3/2001 regarding the formation of the agency for national coordination of disaster relief and refugees (Bakornas PBP). Flood risk management mainly focused on structural protection. One semester after the February 2002 flood, Jakarta administered the formation of the committee at provincial level through the Governor decision No. 96/2002 regarding the formation of a committee for the administration of disaster relief and refugees (Satkorlak PBP) dated 24 Juli 2002. The formation was initiated by the pressure following the flood case 2002. By 2007 a river flooding early warning system (preparedness alarm 1-2-3-4) was available as well as national and provincial flood committees (Grenti, 2016). In 2008, the national government formed a special agency namely the Agency for Disaster Management (BNPB) to replace the committee. Following the new policy, the provincial government administered the local agency for disaster management (BPBD Jakarta) through Provincial regulation No. 9/2011. By 2013, national and provincial disaster management agencies, as well as flood risk mapping tools were developed (BNPB, 2016).

Flood risk has gained the attention of national policy making (Bappenas, 2010). With the help of UNDP and the World Bank, Bappenas and BNPB started to develop a tool to assess risk, which became the InaRISK/InaSafe web platform announced on 10 November 2016 (BNPB, 2016). InaRISK is an initiative to present disaster risk maps for Indonesia. The platform is aimed at being a tool for disaster management.

In terms of socioeconomic development, Jakarta's GDP has been growing almost 0.27 percentage points higher on average compared to the rest of the country (6.14% compare to 5.87% during 2007-2013) (Bank Indonesia, 2014). This has led to increased urbanization (e.g. Robo et al., 2018).

Event comparison in respect to riverine flood hazard

Riverine floods in Jakarta have so far been initiated by high precipitation either in the upland area and/or in the city itself. Precipitation preceding the three flood cases in 2002, 2007, and 2013 were 362mm over 10 days (Bappenas, 2007), 327mm over 6 days (Bappenas, 2007), and 250-300mm over 15 days (Pertiwi, 2013) respectively. These are estimated to equate to flood return periods of 50 years (Bappenas, 2010), 50 years (Bappenas, 2010), and 30 years

(Budiyono et al., 2016) respectively. The inundation extent of the city has been estimated at 25.3% (2002) (Budiyono et al., 2016), 36.0% (2007) (Budiyono et al., 2016), and 6.2% (Evan, 2015).

A specific feature of the 2013 event was a dike break that occurred on the Western Flood Canal (Afrianto et al., 2015) within the business area up to the presidential palace. The dike break occurred at the beginning of the Western Flood Canal. The dike break occurred as a result of the turbulence of high water near a bridge pole, which led to overtopping and failure. The overflowing water then flowed along streets as far as 5 km, passing the major business district in Jakarta to the presidential palace (Djamaluddin, 2013).

Event comparison in respect to exposure

Information on the exposure to the three floods can be found in Table 2. Note that the 2002 and 2007 events occurred during a time when disaster events were not assigned to a certain institution. For example, Bappenas (2007) reports different numbers of displaced people for the 2002 flood depending on the quantification method used. This applied also for data by BNPB since the office was established in 2008. In general, BNPB and Bappenas also carried different mandates to the country. Bappenas produced data in the light of national planning, while BNPB for emergency response.

Table 2. People exposed to the flood events as recorded by BNPB (2017) database (first record) and reported by Bappenas (2007) (second record). There is no information how BNPB collects 2002 and 2007 data, since the agency was not formed yet.

Event year	Mortality	Wounded	Missing	Sickness	Displaced
2002 (50 FRP)	80	4,897/na	0/na	0/na	154,270
2007 (50 FRP)	79	484/na	na/na	na/na	590,407
2013 (30 FRP)	38	0/na	0/na	105,987/na	87,291 (Evan, 2015)

Jakarta's population in 2002, 2007, and 2013 was 7.46 million, 9.06 million, and 9.99 million respectively. This means that the capital's population grew about 4.2% per annum during 2002-2007 but then slowed down to 1.7% (BPS Provinsi DKI Jakarta, 2014). In the 2013 flood event, notably there was a lot of basement inundation of high rise buildings (BPBD, 2013).

Event comparison in respect to vulnerability

Jakarta's largest flood prior to 2002 occurred in 1996. Since then there have been many local adaptations to floods. Inhabitants around riverbanks in the country have traditionally recognized self-organized flood early warning systems using bamboo gongs (Budiyono, 2018) or other means (Voorst, 2015). The formal organization of an early warning system in Jakarta was started in 2006 in the form of water level information at the upland flood gate to the downstream flood guards (e.g. Grenti, 2006). The upland-lowland water level information dissemination was established at eight points in the upland locations (BPBD Provinsi DKI Jakarta, 2013) that guarantee up to nine hours of lead time. In particular, for flooding along the Ciliwung catchment flood damage in 2007 and 2013 may have decreased as a result of the early warning system. The early warning system has been reported as being effective for residents along the riverbanks (Voorst, 2015; Hellman, 2015).

Table 3: Summary of vulnerability-related aspects

Type	2002	2007	2013
Awareness and precaution	Limited	Store important stuff on higher level ground/building, prepare door frame with personal dike (Budiyono, 2018)	Store important stuff on higher level ground/building, prepare door frame with personal dike (Budiyono, 2018)
Preparedness	Limited	Community organised early warning based on upland water level monitoring (Grenti, 2006)	Community organised early warning based on upland water level monitoring (Grenti, 2006); flood risk mapping tool developed (BNPB, 2016)
Organisational emergency management	Limited	Emergency response regulation amended by Bakornas PBP (national level) (Keputusan Presiden No 3 Tahun, 2001), and its implementation by Satkorlak PBP at provincial level (Keputusan Gubernur No. 96 Tahun, 2002)	Emergency response on damaged/destroyed buildings by BNPB (national) (Peraturan Presiden Nomor 8 Tahun, 2008), based on report by BPBD (provincial) (Peraturan Gubernur Provinsi DKI Jakarta Nomor 26 Tahun, 2011); Regular capacity building programs by BPBD (provincial)
Coping capacity	No information	No Information	No Information

Summary

The three flood events of 1 February 2002, 1 February 2007, and 16 January 2013 in Jakarta are the most devastating riverine floods in the history of Jakarta. The magnitude of the floods in terms of their return periods are estimated at 50, 50, and 30 year return periods respectively. Measures have been taken to reduce the risk over the intervening period. The 2013 case was a special case, in that there was also a dike break on the Western Flood Canal.

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ID 5

Paired coastal flood events: 1990 and 2013 coastal floods in North Wales, the United Kingdom

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Short description of both events with a focus on impacts

In February 1990, a combination of high tide and extreme weather caused overtopping and breaches of defenses in North Wales. Areas of Towyn, Ffynnongroew, Rhyl and Prestatyn were flooded (Jones, 1990). The seawall protecting Towyn from the sea was breached causing inundation up to 2 km inland. More than 5000 people had to be evacuated and damages were estimated to be more than £ 50 million (HR Wallingford, 2008). For comparison with the 2013 event, after correcting for inflation this corresponds to £ 47 million in 2015 values.

In December 2013, the United Kingdom was hit by severe flooding. Although North Wales was not one of the most severely hit areas, surges were said to be similar to the ones experienced in 1990 (Towyn and Kinmel Bay Flood Planning, 2015). The same area in Rhyl, around Garford road, that was flooded in 1990, was flooded in 2013 (BBC, 2010; Natural Resources Wales, 2014b). Over 300 people were evacuated and damages were estimated to be between £23 and £33 million for the 2013 and 2014 winter floods in North and West Wales together (thus the damages were less than that for the floods in North Wales) (Environment Agency, 2016). For comparison with the 1990 event, after correcting for inflation this corresponds to £ 22 to 32 million in 2015 values.

Descriptions of processes between events with a focus on risk management

In between the flood in 1990 and 2013, the Welsh government and other organisations invested a substantial amount in (maintenance of) the defense systems around the coast (Natural Resources Wales, 2014a). The Environment Agency Wales (now Natural Resources Wales) reports spending £20 million on maintaining and increasing defences in 2008-2009 alone (Environment Agency Wales, 2009). Forecasting and warning processes were upgraded and a lot of effort has been made to increase public awareness of flood risk and resilience to flooding (Natural Resources Wales, 2014a). Because of this, in 2008, 57% of the at risk population in Wales was aware they were living in an area at risk. Of those 57%, three out of five of the people had taken measures to prepare for flooding (Environment Agency Wales, 2009). Cooperation and relationships among professional partners responsible for the various tasks concerning flood risk (forecasting, emergency management, recovery, etc.) have been improved and helped to manage the 2013 event in a better way (Natural Resources Wales, 2014a).

Event comparison in respect to hazard

In 1990 a high tide of 11.06 m chart datum (CD) at Liverpool and a storm surge of 1.3 m in combination with waves of up to 4.5 m high caused defences to breach at Towyn (HR Wallingford, 2008). A 450 m long breach in the sea wall caused an area of up to 2 km inland to be flooded with water depths getting as high as 1.8 m. Other areas along the coast of North Wales, including Rhyl, were also flooded. In Rhyl, defences were overtopped causing the area around Garford road to be flooded. The return period of the combination of tide and surge conditions was estimated to be 1 in 500 years.

In 2013, conditions in Liverpool bay were similar to 1990 (http://your-biz.org/high-tide/), with a high tide of 11.15 m CD at Liverpool and a storm surge of 1.08 m (Sibley et al., 2015; Wadey et al., 2015). No severe breaches occurred, but again areas along the coast of North Wales experienced severe flooding. A 10 m dike breach caused agricultural land to flood (Natural Resources Wales, 2014a). In Rhyl, overtopping of defences caused flooding of the same area that flooded in 1990. After the 1990 event a storage lagoon had been designed to protect the properties in Rhyl from flooding. However, the system did not function properly, because gates in the sea wall were not closed and the outflow of the storage lagoon was blocked by debris (Natural Resources Wales, 2014b).

Event comparison in respect to exposure

In 1990 the hotspot was the town of Towyn, where defences breached causing the land behind those defences to be flooded. Because of this breach the number of people affected was very high: over 5000 people had to be evacuated from 3000 properties (HR Wallingford, 2008). Because defences were upgraded and much better maintained in 2013, there were no major breaches during this event and therefore the number of people affected was lower. However, some smaller breaches did occur. 400 people had to be evacuated and more than 300 properties were affected, most of them in Rhyl, in the same area that was flooded in 1990 (BBC, 2013; Natural Resources Wales, 2014a).

Event comparison in respect to vulnerability

According to the Wales coastal flooding report impacts of the 2013 event would have been much worse 10 or 20 years ago (Natural Resources Wales, 2014a). This indicates that in between the two events in 1990 and 2013 substantial improvements to vulnerability have been made in order to reduce the impact of big events. Awareness and information campaigns had increased the public's awareness of the risk and their preparedness. In 2013, 125 properties were not affected by flooding because they had taken precautionary measures to protect their properties (Natural Resources Wales, 2014a). The flood warning system had significantly improved, following investments in the years in between the two events. In 1990 no warning was given, while in 2013 most areas were warned well in advance, with warnings for general areas of concern given three days in advance and specific warning one day before the event (Natural Resources Wales, 2014b). The area in Rhyl that was flooded did not receive a flood warning, because forecasts did not predict water levels higher than the warning levels. However, the local water levels were much higher because of waves caused by local wind conditions (Natural Resources Wales, 2014b) and around 400 people had to be evacuated from their houses (BBC, 2013). In 1990, flood response and recovery actions and organisations were mobilized on a more ad hoc basis. Given the lack of planning and management beforehand, they did a good job (Jones, 1990). However, the Civil Contingencies Act that came in to force in 2004, required agencies to put into place a framework for cooperation in case of emergencies, which ensured that the emergency response and recovery in 2013 was better coordinated (Natural Resources Wales, 2014b).

Summary

Flood risk has been reduced in North Wales due to a combination of society and agencies being made aware of the risk after the 1990 event and a general increase in attention to flood risk management in the United Kingdom. In general, reductions in loss can be attributed to a learning effect, either because of a local event or because of an increase in events and climate change in the United Kingdom in general. Because of substantial investments in structural flood protection, flood forecasting and warning systems and awareness campaigns, in North Wales the consequences of the 2013 flood were much less severe than the consequences of the 1990 flood.

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ID 6

Paired drought events: 1998 and 2013 meteorological droughts in Central Chile

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Short description of both events with a focus on impacts

We report the impacts from two of the main meteorological annual droughts over the last century in central Chile: 1998 drought and 2013 drought (see hazard description section for further details on these events).

The meteorological deficits from both events were experienced by most of the country, however, we concentrate the impacts analysis on the Maule region. The most affected economic sectors during these events were agriculture and electricity, which correspond to the main economic activities in Maule region.

The Maule region covers 30,296 km^2 (4% of the national territory, excluding the Chilean Antarctic territory), and has contributed approximately 14% and 11% to the national GDP over the last 20 years for the electricity and agricultural sectors, respectively (Figure 1). In this same time period, the national electricity and agricultural sectors have contributed in average 2.8% and 3.5% to the national GDP, respectively.

The 1998 drought caused a 12% and 4% decrease in energy and agriculture GDP regional contribution to the national GDP per corresponding sector, respectively (computed as the difference between 1999 and 1998 values from Figure 1).

Following the 2013 drought, the energy GDP contribution increased in 13%, while the agriculture GDP contribution decreased in 12% (computed as the difference between 2014 and 2013 values from Figure 1).

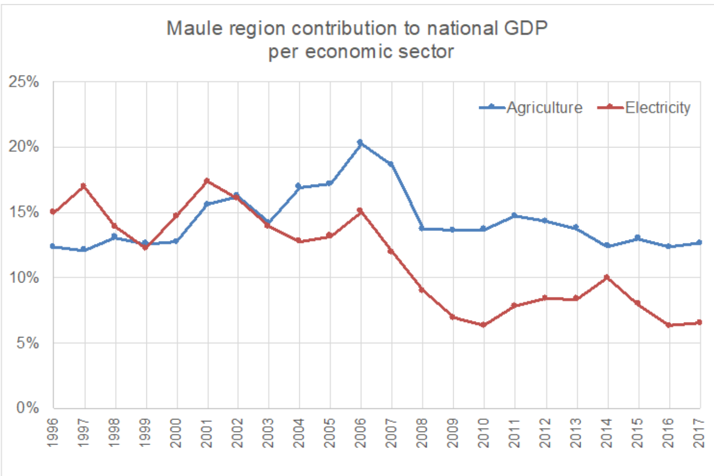

Figure 1: Maule contribution to national GDP per economic sector (data obtained from Banco Central de Chile, 2020).

As a consequence of the precipitation deficits and lack of snow accumulation during the 1998 drought, the main hydro-power and irrigation reservoirs were not replenished during the wet season. These drought-related impacts, in combination with deficient reservoir management practices, repeated failures of thermal power plants, and delays in the commissioning of natural gas power plants, led to a severe electricity crisis in 1999, with 1,200,000 users affected by hourly power outages (Rozas, 1999) within the study area. Agriculture was also affected during this year. Fruit size was smaller, and sensitivity to pests and diseases increased (SNA, 1998).

By contrast, the 2013 drought (and the megadrought in general) did not led to electricity crisis, although other sectors of society were impacted, particularly agriculture and water supply systems for human consumption. The reduced impacts on energy generation from the 2013 drought compared to the 1998 drought may be explained by several factors, including: the lower precipitation deficits in 2013 compared to 1998; better reservoir management practices in the context of consecutive dry years; and most importantly, the evolution of the energy generation matrix in those 15 years (see section 2 for further details).

The impacts of 2013 drought in agriculture were experienced not only in Maule region. In fact, from Coquimbo to the Araucanía regions (29-41ºS, an area of 187,000 km^2, Figure 3), with 6 decrees of water scarcity, 162 counties declared under agricultural emergency, 18,613 M US$ spent in related emergency and mitigation measures, and ~20 M US$ for supplying drinking water to ~100,000 families in rural communities by using water trucks (Garreaud et al., 2017; CIPER, 2017; UNEA, 2014).

It should be noted that the impacts reported here are mainly due to deficits in water supply, which actually represent hydrological droughts. However, the drought description and quantification are provided in terms of the meteorological droughts that caused those hydrological droughts.

Descriptions of processes between events with a focus on risk management

In 2005, Chile signed the Hyogo Framework for Action (https://www.eird.org/cdmah/), but only since the earthquake in 2010 Chile has taken serious steps to adopt a prospective approach to disaster management. In order to comply with the international commitments acquired by Chile in 2005, the National Policy for Disaster Risk Management (ONEMI, 2016) was decreed to serve as a guiding framework to the State institutions to reduce impacts and to respond properly to emergency situations in the country. From this policy, several national plans for disaster risk management of specific disasters have been developed (e.g., wildfires, tsunamis, landslides), however, hydro-meteorological hazards (including droughts and flooding) still do not have a specific National Plan for Disaster Risk Management. Further, the legal framework to deal with natural disasters in Chile is quite fragmented. The official recognition of a drought condition that affects the country, as well as the response mechanisms to deal with it fall fundamentally on four Ministries: i) Ministry of the Interior and Public Security, ii) Ministry of Energy, iii) Ministry of Public Works and iv) Ministry of Agriculture.

The Ministry of Interior declares "drought conditions" through the use of the "Catastrophe Zone Decree" (Supreme Decree No. 104/1977 and Law No. 16,282 / 1965). This decree creates a state of constitutional exception (Law No. 18.415 / 1985) through which the exercise of people’s rights and guarantees can be affected in order to protect them during the catastrophe.

The Ministry of Energy can activate the Rationing Decree (DFL 4/20.018) after a report from the National Energy Commission, when a generation deficit occurs or is projected as a result of prolonged power plant failures or drought situations. This article, in spirit, form and substance, has not varied significantly with respect to Article 99 bis of the General Electric Services Law of 1959.

In the case of the Ministry of Public Works, the General Directorate of Water (DGA) can qualify drought periods as extraordinary (article 314 of the Chilean Water Code; DGA, 2012). With this qualification, the President of the Republic can declare areas of water scarcity. The classification of periods of extraordinary drought by the DGA is based on the analysis of standardized drought indices (SPI and SRI).

The Ministry of Agriculture is the public entity that has shown the greatest evolution to support a prospective approach to Drought Risk Management. This transformation has been fundamentally marked by the creation of a "Presidential Commission for Drought / Agroclimatic Risk Management" and the parallel creation of an operational unit. The risk of droughts has been managed with the declaration of "Agricultural Emergency" (MINAGRI, 2009), which stipulates a response mechanism from the Public Sector Budget Law. In parallel, this Ministry has been responsible for managing the Agroclimatic Observatory (https://www.climatedatalibrary.cl/UNEA/maproom/, launched in 2013), which has become an effective management tool for Drought Risk Management in the country. The development of this observatory is a unique experience in Chile, and the result of the collaborative effort of a large number of national and international institutions aimed at creating a public platform for informed decision making based on science.

In terms of infrastructure, the reservoir capacity increased slightly, from 4,000 Mm^3 in 1998 to ~4,500 Mm^3 in 2013 (MOP, 2010). However, in order to alleviate drought risk and to respond to the increasing demand, the energy generation matrix was significantly expanded, while becoming less vulnerable to droughts. Although this evolution seems to be in line with the challenges of facing the drying projections for the XXI century in Chile, it has been at the expense of increasing the energy generation based on fossil fuels (Figure 2). In 1998, the electrical generation was 61% and 39% based on hydroelectricity and fossil fuels -based power plants, respectively. In 2013, these percentages were inverted.

With respect to external drivers, the climate change context installed over the last couple of years has boosted the national awareness and quantification of carbon footprints, which will pose key challenges and pressure to the current energy generation matrix. While the non-conventional renewable energy (NCRE) sources has increased since 2013 reaching a 19% of the installed capacity, the mitigation strategies pledged in the Nationally Determined Contributions of Chile aim at becoming carbon neutral by 2050 (NDC, 2015, retrieved from https://unfccc.int).

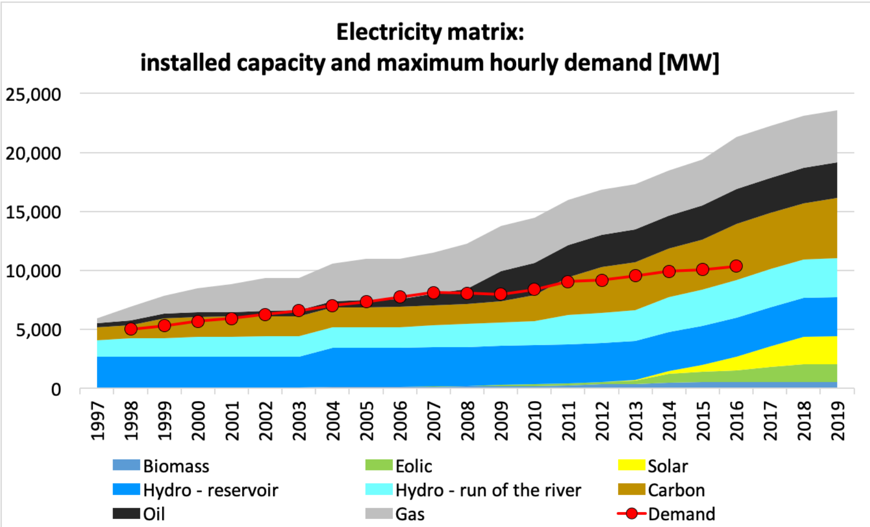

Figure 2: Electricity matrix in Chile: installed capacity and maximum hourly demand (data retrieved from https://www.cne.cl/estadisticas/electricidad/produccion_real_por_sistema/).

The Chilean population and environment also changed during the 15 years in between the two drought events. The main land use change in South-Central Chile was the increase in forest cover, largely dominated by the expansion of exotic plantations, rather than native forest regeneration (Nahuelhual et al., 2012; Heilmayr et al., 2016). From 1998 to 2013, the population density slightly increased from 20.14 to 23.63 in/km^2, but the GDP per capita increased 3-fold, from 5,446.8 to 15,842.9 US$, respectively (World Bank, 2019). In addition, the Chilean society underwent a consistent increase of awareness and demands for sustainable development. For example, a major hydropower project from Endesa and Colbun companies, including 5 large reservoirs in Patagonia was cancelled in 2014. This decision was made after 7 years of project design, with a company cost of US$320 millions, and despite being approved by the corresponding national institutions in 2011. The social pressure, with strikes that summoned more than 50,000 people, was a key factor in the decision of revocating the environmental permit in 2014 (Astorga, 2013).

Event comparison in respect to drought hazard

In Chile, 1998 was the second driest year (in terms of precipitation deficits) over the last century, with a regional precipitation index (RPI) of 32% (Figure 3 from Garreaud et al., 2017). This regional precipitation index was defined as the median of annual rainfall records standardized by their corresponding climatological values (1970-2000 mean) from seven meteorological stations between 32 and 37ºS with complete records from 1915.

The 2013 event was a less severe meteorological drought than the 1998 drought (RPI = 56.2%), but it followed three consecutive years with precipitation deficits in central Chile (RPI = 72.22, 65.25 and 72.60 for the years 2010, 2011 and 2012, respectively). The 2013 event has been one of the driest years within the Chilean megadrought, which started in 2010 and continues up to date in Central Chile (Garreaud et al., 2017).

For both events, the precipitation deficits were experienced by most of the country, as shown by the standardized precipitation index (SPI) and the standardized precipitation evaporation index (SPEI) were computed for the national territory based on the CR2MET dataset (retrieved from http://www.cr2.cl/datos-productos-grillados/) (Figure 3). The 1998 precipitation deficits were more severe than in 2013, which resulted in more severe SPI values, and larger areas affected by extreme droughts. The 2013 event, while featuring less precipitation deficits than the 1998 event, it showed higher evaporation rates between 28 and 32S (Coquimbo region), and thus more severe SPEI indices in that area.

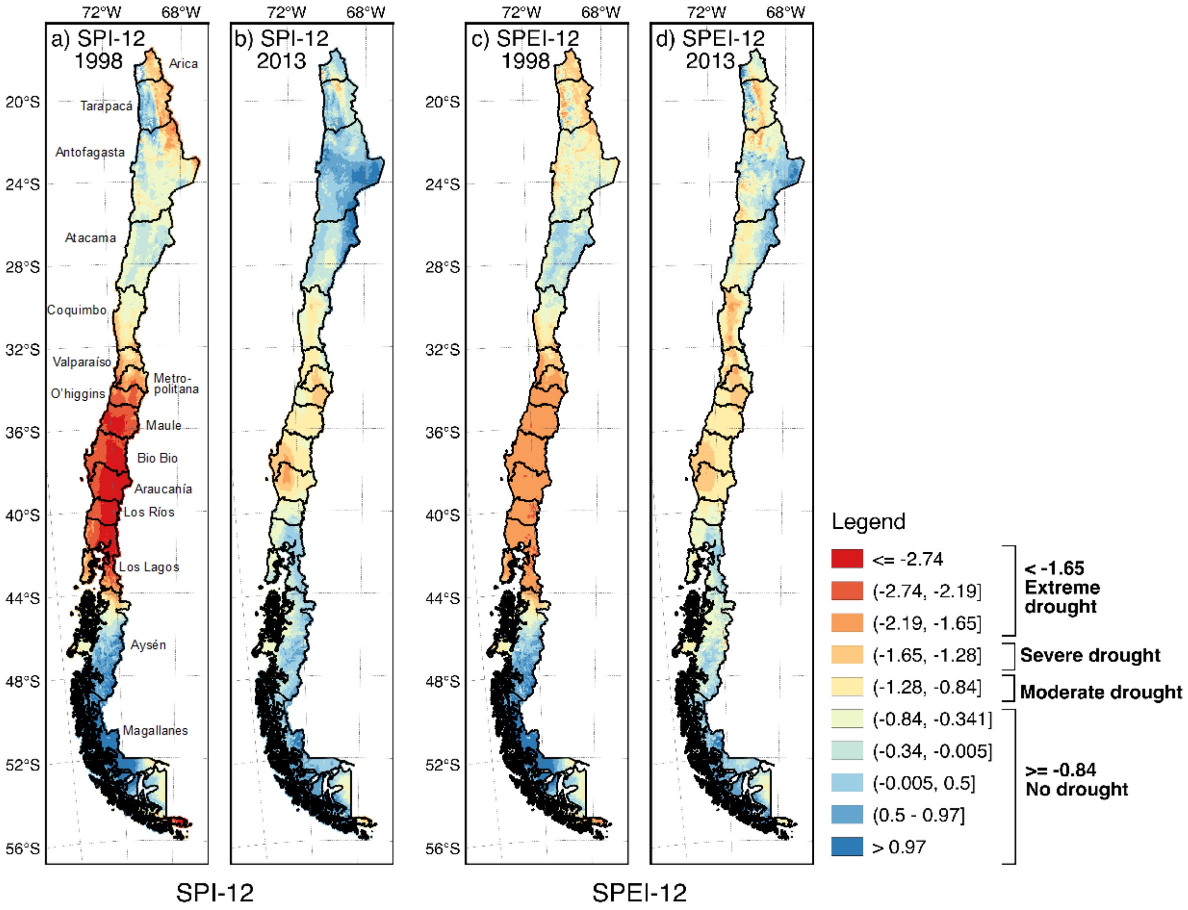

Figure 3: SPI-12 and SPEI-12 indices computed in December 1998 and December 2013.

Event comparison in respect to exposure

According to the agricultural census, the Maule region had 3,591 and 7,683 hectares of irrigated area in 1997 and 2007, respectively (INE, 2020). This means an increase in irrigated agriculture of approximately 113% between the two drought events.

The population of the region increased approximately in 15% between drought events, with 908,097 people in 2002 to 1,044,950 people in 2017 (INE, 2020).

The drinking water supply system in the region has relied mainly on sanitary water companies (82% in 2002, and 90% in 2017), and pumping wells (14% in 2002, and 7% in 2017).

Regarding critical infrastructure, this region has two reservoirs used for hydroelectricity generation and irrigation: Colbun (1,544 Mm^3 capacity,) and Laguna Maule (1,420 Mm^3 capacity). In addition, there are three smaller reservoirs used for irrigation: Digua (255 Mm^3 capacity), Bullileo (60 Mm^3 capacity) and Tutuven (22 Mm^3 capacity).

The two main reservoirs, Colbun and Laguna Maule, reached their highest deficits in 1999, following the 1998 drought (78% and 94% deficits on stored volume, respectively). At the end of 2013, these reservoirs had 49% and 83% deficits, respectively (DGA, 2020).

Event comparison in respect to vulnerability

The level of vulnerability awareness from society, public institutions and private sectors of the economy increased after 1998. However, most natural hazards, including droughts, have not been foreseen, therefore the measures to tackle the associated crisis have been mostly reactive, and based on short-term approaches. For example, the measures applied to address the energy crisis in 1999 (triggered by the 1998 drought) included: the dictation of energy supply rationing decree, which authorized energy companies to schedule voltage reductions and outages in power supply; the dictation of water shortage decree of the South and Central Chile, which allowed the use of water allocated to irrigation for hydroelectric generation; and energy saving campaigns (Rozas, 1999).

From a preparedness perspective, in the last decades, the Food and Agriculture Organization of the United Nations (FAO) has supported risk management for extreme weather impacts in Chile. This collaboration has already shown results in the improvement of public management and policy recommendations. FAO's collaboration was extended to a second stage for the design and implementation of the National Agroclimatic Risk Management System. This system will identify the main vulnerable aspects in the different territories, aiming at minimizing the occurrence of national emergencies, reducing the impacts of extreme weather events on the most vulnerable populations, and avoiding economic losses (Meza et al., 2010).

A recent study indicates that 44% of the problems related to water scarcity in Chile are still derived from failures in **water management** and **governance** (Fundación Chile, 2019). This includes the lack of transparency of the water market at the basin level, the lack of coordination of the institutions at the basin level (restricted to water resource management by administrative sections), limited user control; and limited, fractional and contradictory information on water resources (generating distrust among the actors). Another 17% is caused by the increase of productive activities and the overloading of water use rights, while 14% is caused by the use of chemical products in agribusiness, mining environmental liabilities, lack of wastewater treatment in rural areas and the decrease in quality due to a decrease in aquifer levels and saline intrusion.

Summary

The two events presented here reveal important information about the evolution of a developing country facing natural hazards. Clear limitations in drought risk management are identified. Although there have been improvements in the legal framework and institutional organization to manage and prepare for natural hazards in the 15 years between events, droughts are still not well foreseen, and mainly managed with short-term reactive measures.

While the 2013 event places agriculture as the main affected sector of the economy, we argue that the de-carbonization process that Chile must pursue in the following years will challenge the energy sector to advance towards a matrix that does not rely on fossil fuels, and that should be resilient to the drying projections of the country.

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ID 7

Paired drought events: 1976 and 2018 droughts in the Lorraine Region, France

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Short description of both events with a focus on impacts

The Lorraine Region is located in the North-East of France (fig. 1). Mean annual rainfall is around 900 mm (1900-2018). According to Köppen classification the climate type is Cfb (i.e. oceanic climate with warm summers) and rivers have temperate oceanic hydrological regime. Two meteorological and hydrological drought events that affected the Lorraine Region are here compared: 1976 and 2018. Both droughts had serious impacts on agriculture with low yields especially for fodder (Direction Régionale de l'Alimentation, de l'Agriculture et de la Forêt 2019, Ministère de l'agriculture et de l'alimentation, 2018). Both events also affected forest especially young plants because of hydric stress caused by low soil moisture (Direction Régionale de l'Agriculture et de la Forêt Lorraine n.d., Département de la santé des forêts 2019). In 2018 parasites also affected the forest. Rivers recorded in both cases very low water levels that resulted in lower hydroelectric power production (Agence de l'Eau Rhin-Meuse 1977, RTE 2018). Impacts differ in terms of water shortages, important in 1976 (Agence de l'Eau Rhin-Meuse 1977) but rare in 2018. Water supply cut-off and rationing were reported in at least 79 municipalities in 1976 and almost no area was affected in 2018. Degraded river quality was also reported in 1976 with fish death as consequence (Agence de l'Eau Rhin-Meuse 1977). In 2018, many houses cracked because of land movements due to drought and soil rehydration with 66 municipalities classified in "natural disaster" (Legifrance).

Figure 1. Location of the Lorraine region

Descriptions of processes between events with a focus on risk management

The population is stable between 1976 and 2018 (INSEE). Despite an increase in private water consumption (106 liters per day per capita in 1975 and 165 in 2018) due to better standard of living (Observatoire national des services d'eau et d'assainissement) water shortages are only reported in 1976. Indeed, water infrastructures are more developed in 2018 (interconnexion of drinking water network, deeper groundwater pumping) and industrial water requirements are lower. After the second World War the economic development of the Region was essentially based on steel industry and water needs were very high (Garcier 2010). In many cases, industrial water was not simply withdrawn but also consumed. In the post-war years, nearly 100 cubic meters of water were needed to produce one ton of steel (Rogé 1982). Since 1976 industrial activities have strongly declined and consequently reduced water requirement.

Furthermore in 1976 there was no drought monitoring and most measures were taken late. After the 2003 big drought, the French government set up a "national drought plan" based on communication campaigns and water restrictions. A climatological and hydrological monitoring is realized during the drought period to quickly take appropriate measure. In 2018 rivers had very serious low flows but drinking water supply was not compromised and impacts were lower. Regarding agriculture changes, the structure of farms has changed between the two events (less farms but bigger – there were 34 000 farms in 1979 and 7 836 in 2017) (AGRESTE 2019). Both droughts affected seriously agricultural yields. During both events, emergency measures were taken (straw delivered by train from the Marne department (France) and from the Black Forest region (Germany) - (Républicain Lorrain 23rd July 1976) in 1976 and compensation for fodder losses in 1976 and 2018. Finally, since 1982, law on compensation for victims of natural disasters (Law n°82-600, July 13, 1982) has been allowing compensation for cracked house due to land movements related to drought.

Event comparison in respect to drought hazard

The main difference between these events is that the first one started early (rainfall deficit occurred from January to August) and the second one begun very late (rainfall deficit from June to November). Rainfall deficit started in January in 1976 and in June in 2018 (fig. 2). The rainfall deficit was extreme from January to June in 1976 and from June to November in 2018. Cumulative rainfall January to June: 256 mm in 1976, 535 mm in 2018 and 433 mm for the average 1900-2018. Cumulative rainfall from June to November: 254 mm in 2018, 382 mm in 1976 and 465 mm average 1900-2018). SPI-3 for the years 1976 and 2018 are compared on figure 3. In 1976 the SPI is below normal nearly the whole year whereas in 2018 it was positive until May and the deficit started in June and was extreme in September and October and lasted until November. Sunshine was higher than normal from March to August in 1976 and from June to October in 2018. Table 1 shows that 2018 was clearly warmer than 1976 with high temperatures from April to December.

Monthly river flows of the Moselle river in 1976 and 2018 in respect to the period 1961-2018 are presented figure 4 at Toul and figure 5 at Hauconcourt. Catchment area of the Moselle at Toul is around 3340 km² and 9400 km² at Hauconcourt. At Toul, the monthly minimum flow was extremely low in 2018 and below 1976. The minimum occurred very late (minimum occurred in August in 1976 and October in 2018). In 1976 extreme flows ended in September. At Toul, river flows are not yet influenced by Vieux Pré reservoir whereas at Hauconcourt the Moselle flows are regulated since 1993. Monthly flows at Hauconcourt show the impact of the dam regulation with flows higher than in 1976 and not so extreme.

Figure 2. Monthly rainfall for the years 1976 and 2018 compared to 1900-2018 average – Data source: Delus et al. 2018

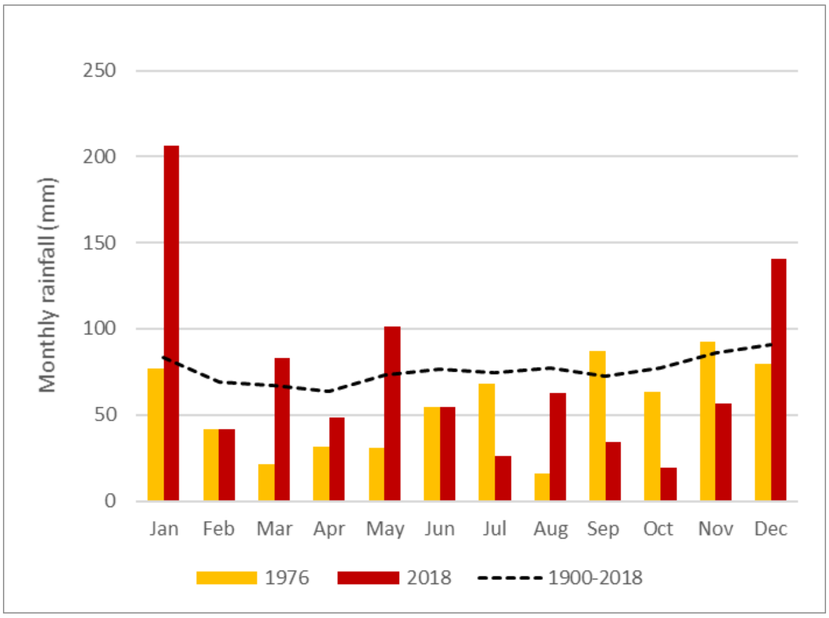


Figure 3. Comparison of SPI3 for the years 1976 and 2018 (1900-2018) – Data source: Delus et al. 2018

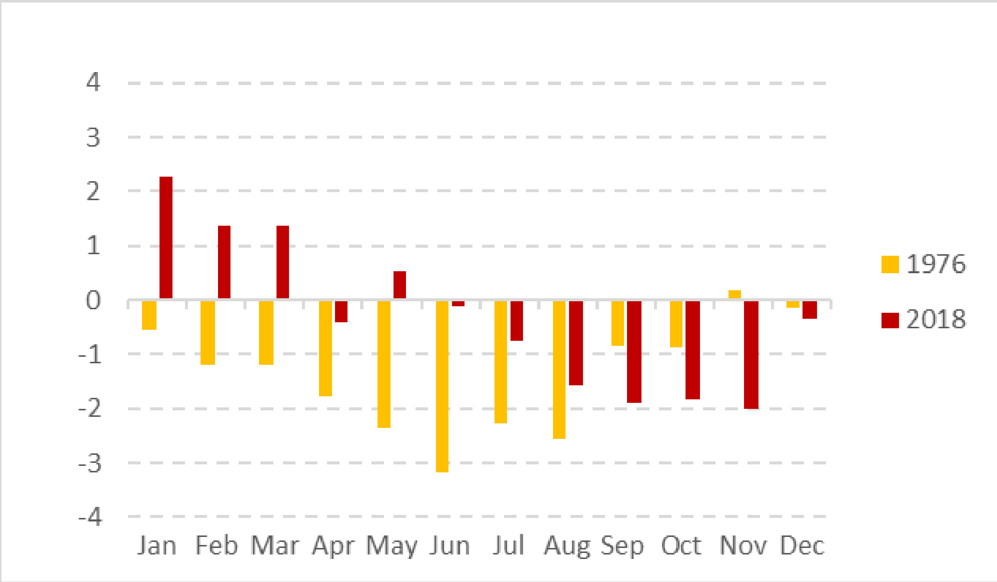


Table 1. Mean monthly temperature in the years 1976 and 2018 compare to 1900-2018 period – Data source: Delus et al. 2018

	T mean (°C) 1976	Δ T°C 1976 compare to 1900-2018	T mean (°C) 2018	Δ T°C 2018 compare to 1900-2018
Jan	1.9	+0.9	5.7	+4.7
Feb	2.4	+0.4	-0.3	-2.2
Mar	3.8	-1.5	4.6	-0.7
Apr	7.9	-0.8	12.6	+3.9
May	13.3	+0.3	15.6	+2.6
Jun	18.2	+2.2	18.3	+2.2
Jul	19.7	+1.7	21.5	+3.5
Aug	17.0	-0.4	20.2	+2.8
Sep	13.0	-1.2	16.0	+1.8
Oct	10.5	+0.8	11.6	+1.9
Nov	4.8	+0.0	6.8	+2.0
Dec	0.1	-1.8	4.3	+2.3

Figure 4. Monthly flows of the river Moselle at Toul station in the years 1976 and 2018 (reference period 1961-2018) - Data source: Banque hydro

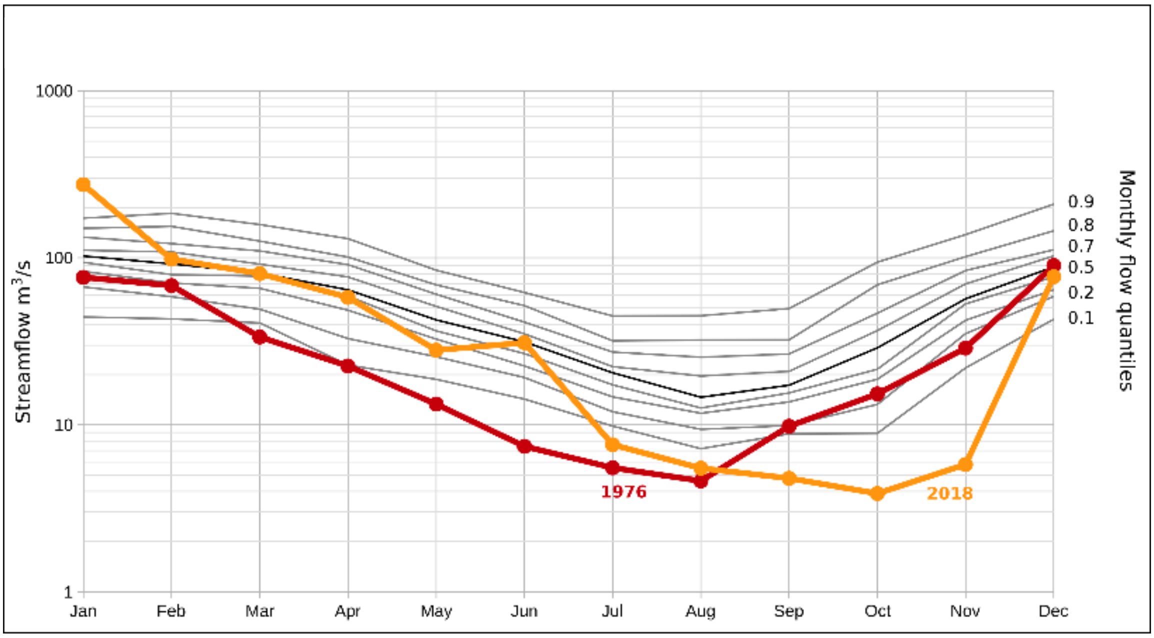
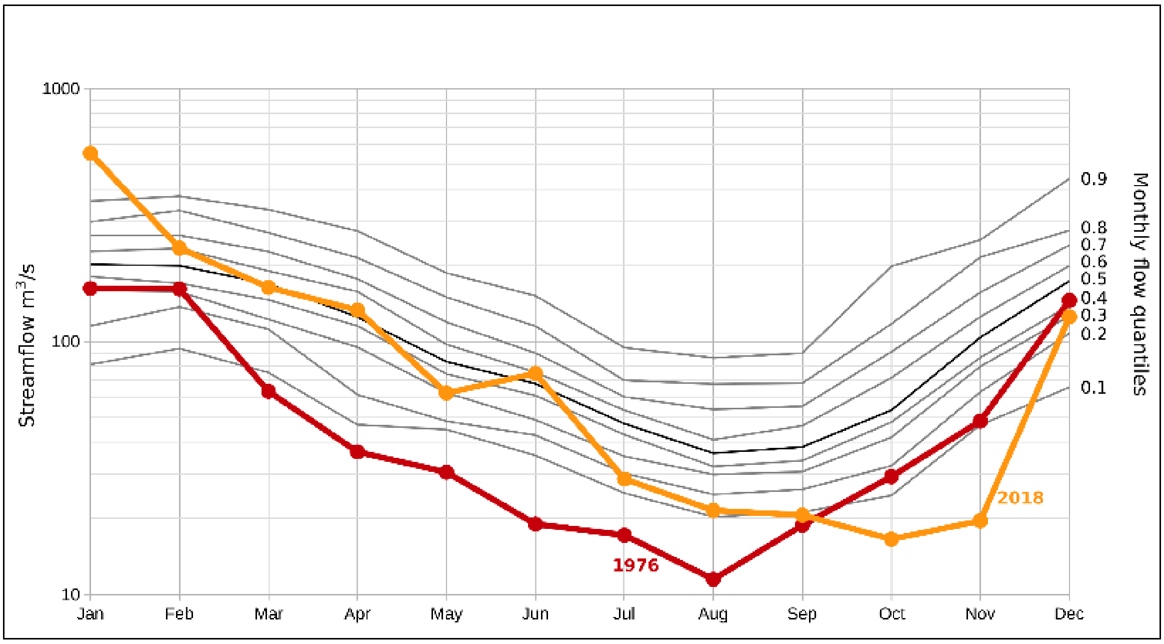


Figure 5. Monthly flows of the river Moselle at Hauconcourt station in the years 1976 and 2018 (reference period 1961-2018) Data source: Banque hydro



Event comparison in respect to exposure

In 1976 the drinking water supply was an exposure hotspot to drought especially in rural and industrial area because of insufficient drinking water network to satisfy the water demand (Mission interministérielle de l'eau 1977; Agence de l'Eau Rhin-Meuse 1977). The 1976 drought highlighted these lacks and afterwards water infrastructures were improved (interconnexion of drinking water network, deeper groundwater pumping) to guarantee enough water resources during low water period. Furthermore since 1993 Vieux Pré reservoir provides water for the cooling circuit of a nuclear power plant. This reservoir is also used to regulate the Meurthe and Moselle river flows during low water periods.

Event comparison in respect to vulnerability

Following the 2003 drought a national drought plan was set up in France with a meteorological warning system for heatwave managed by the French meteorological organization (Meteo France) and low water monitoring made by water managers (DREAL Grand Est). Both are available online and meteorological as well as hydrological bulletin are published during drought periods (Propluvia, Direction Régionale de l'Environnement de l'Aménagement et du Logement, 2018)). Many communication campaigns are made in the framework of the drought plan as well as advices and water-use restrictions. The vulnerability was high in 1976 but reduced in 2018 due to the national drought plan. Measures defined by the drought plan and applied in 2018 were, for example: ban on filling private pools; vehicle washing only allowed in stations with water recycling system; ban on irrigation, watering private or public grass, vegetable garden, green spaces and playing fields (except for national competitions) between 9:00 am and 8:00 pm; water use limited to the bare minimum for industry; limited withdrawals for water canal supply and reduction of maximum draught; hydroelectric power plants stopped if minimum acceptable flow exceeded.

Summary

The 1976 and 2018 droughts had both extreme low flows but impacts in 2018 are lower than in 1976 thanks to the reduction of the vulnerability. First the 1976 event highlighted a lack of drinking water resources in case of severe drought. Following this drought, water infrastructures were developed to increase water supply. In 2003, about 15 to 20 000 people died due to the heatwave. This event drove to the setting of a "national drought plan". In 2018, the drought affected agriculture and caused cracked houses but financial supports were allowed through different government emergency plans. However, the successive 2015, 2017, 2018 and 2019 droughts will probably lead to agricultural adaptation questions.

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Heatwave plan: https://solidarites-sante.gouv.fr/sante-et-environnement/risques-climatiques/article/le-plan-national-canicule

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Legifrance : https://www.legifrance.gouv.fr/

Ministère de l'Agriculture et de l'Alimentation : https://agriculture.gouv.fr/

Ministère des Solidarités et de la Santé : https://solidarites-sante.gouv.fr/

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ID 8

Paired drought events: 1947 and 2018 droughts in Baden-Württemberg (southwestern Germany, Europe)

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Short description of both events with a focus on impacts

The drought events of 1947 and 2018 had similar impacts on agriculture and forestry. In both cases a deficit of precipitation led to a serious hydrological imbalance, affecting soil moisture and streamflow in rivers, lakes, and groundwater levels. Reduced crop productions and high losses of yield (e.g. potatoes or rapeseed) were reported. In 1947, several cases of complete failure of harvest were documented, with consequences for food supply. Especially cities were affected by the supply crisis. Conflicts occurred between the rural and urban regions (producers and consumers of agricultural products) (Landesarchivverwaltung Rheinland-Pfalz 1947, 1948). In 2018, farmers were impacted and reported crop losses (LUBW 2019, Fig. A1), but no impacts on food supply occurred. In forestry, young trees were particularly affected by both drought events. Around 80 % of newly planted trees in the former American occupation zone of Germany dried up (Deutscher Wetterdienst in der US-Zone 1947, AGDW 2018). Effects on forestry as a result of pests and die-off are still expected to occur a year after the 2018-event. In 1947 fire in villages destroyed agricultural machinery (Deutscher Wetterdienst in der US-Zone 1947).

Hydro-ecological impacts differed e.g., in the case of drinking water supply. In 1947, an increasing shortage of drinking water towards the end of summer was reported. Villages in higher parts of southwestern Germany were without water for weeks and had to be supplied with water from areas miles away (Deutscher Wetterdienst in der US-Zone, 1947). In 2018, only some farms in the Black Forest had to be supplied with water tanks. No other restrictions were reported regarding the supply of drinking water (Köhler A., 2019). During both drought events, **low water levels** in the major river systems led to impaired waterborne transportation. The navigation on the river Rhine was nearly completely halted in October 1947 (Deutscher Wetterdienst in der US-Zone 1947) and severely impaired in 2018 (Mühr et al. 2018). In 1947 and 2018 power plants had to reduce operation significantly. In 1947 this resulted in a partial shut-down of power to households and factories and was followed by orders to reduce power consumption. High losses in industrial production were the consequence. In 2018, impacts on aquatic ecology, recreational water use, and water quality were high on the agenda (Köhler, 2019).

Descriptions of processes between events with a focus on risk management

In 1947, the population of Germany was still dealing with the aftermath of the Second World War (Erfurt et al., 2019). Shortage of fertilizers, lack of workers, unsuitable seeds, and a lack of agricultural machinery contributed to the high crop failures during 1947 (Deutscher Wetterdienst in der US-Zone 1947). The French Allied Control Commission instructed the so-called 'Kartoffelrazzia': in many villages, the actual potato stocks were inspected and partly confiscated and distributed to the urban population (Landesarchivverwaltung Rheinland-Pfalz 1948). With humanitarian aid from abroad school meals were organized (Landesarchivverwaltung Rheinland-Pfalz 1947, 1948). In 2018, losses in agriculture products were compensated by international imports.

From 1947 to 2018 there was a change in the agricultural system. On one hand, the average size of agricultural holdings in BW increased, on the other hand, the number of holdings decreased. In 1949, there were still more than 100,000 farms in BW, in 2018 their number was shrunken to approximately 30,000 farms (with more than 5 hectares of agricultural land each, Statistisches Landesamt Baden-Württemberg 2018).

In 1947, water management was still struggling with the destruction of pipelines during the Second World War (Heyn 1981). An economic boom and a rising population led to a higher demand for water. Due to water supply shortages during 1947 in some regions, discussions started about building what later became the 'Lake Constance long-distance water supply'. This pipeline water supply system was finally established in 1958 and since then transfers' water from Lake Constance over the mountains to drier parts of the state (Heitzmann 2012). In 2018, due to fully functioning water supply systems it was possible to react quickly to water shortages.

Event comparison in respect to drought hazard

For this case study the meteorological drought and the hydrological drought characteristics were studied in more detail. Fig. 1 shows the precipitation and temperature anomalies in BW during the vegetation period (April to October). Comparing the events based on the vegetation period shows that 1947 was drier, but 2018 was warmer. Ranking all years since 1881 based on precipitation, reveals that 1947 was the driest and 2018 the second driest vegetation period on record. Based on the mean temperature (for the same period) 2018 ranks as top one and 1947 as the top two (Fig. 1). Table 1 lists different indices to characterize the meteorological droughts in 1947 and 2018. The 2018-event was drier comparing the following accumulation periods: summer, May to October, and annual. Table 2 presents the monthly average temperature for BW for the years 1947 and 2018. An important precondition in respect to the vulnerability of the population was the extremely cold winter 1946/47. January 1947 ranks as the 13th coldest, February even as the 7th coldest month on record. Fig. 2 compares the SPEI-3 and SPEI-12 for the years 1947 and 2018. Early in the year 2018, the SPEI-3 and SPEI-12 values are above normal. In 1947 only the SPEI-3 value of March was slightly positive. According to the SPEI-1 values, November (1.62) and December (1.75) of 1947 were moderately wet, which resulted in a positive SPEI-3 of December 1947.

Monthly streamflow at gauge Dillingen, Danube River for the years 1947 and 2018 can be compared in Fig. 3 and Fig. A2. Except for four months, the low flow was more extreme in 1947 than in 2018. Especially the low flows of August to September are extremely low (only in March 1947 streamflow was above normal). Towards the end of the year 1947, the low flow situation improved. Ranking all streamflow records for the period March to November since 1901 shows that streamflow from 1947 was the sixth lowest on record (Fig. A2). 2018 ranks as the ninth-lowest on record.

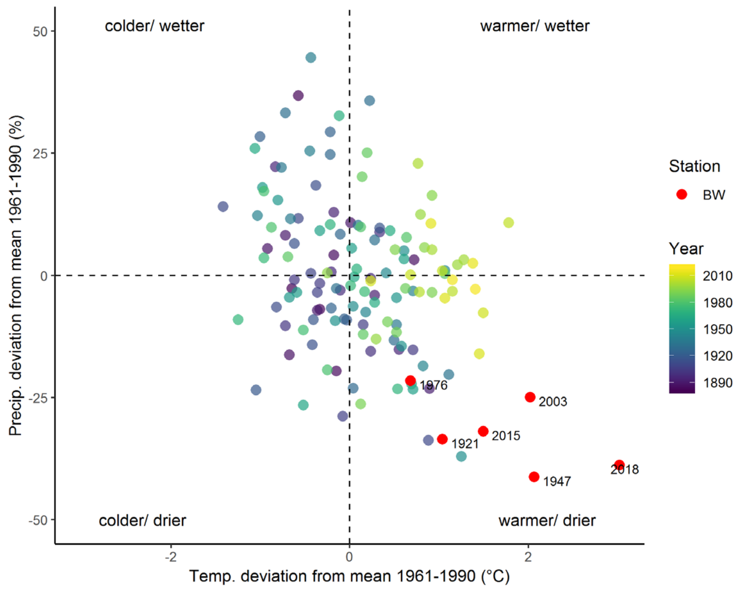

Fig. 1: Precipitation and temperature anomalies in Baden-Württemberg (BW) during the vegetation period (April to October) since 1881. Mean: 1961-1990. Selected extreme years are marked red (data source: DWD).

Table 1: Event comparison in respect to drought hazard. T=Temperature, P=Precipitation, SPI=standardized precipitation index, SPEI=standardized precipitation evaporation index. *Regional average for Baden-Württemberg (data source: DWD, reference period: 1881-2018). See also Fig. 2.

Index	**1946 (Precondition)**	**1947**	**2017 (Precondition)**	**2018**
Summer-P Percentile		0.07		0.02
May-Oct-P Percentile		0.00		0.01
Annual-P Percentile	0.30	0.26	0.56	0.10
Summer-T Percentile		0.02		0.01
May-Oct-T Percentile		0.02		0.00
Annual-T Percentile	0.50	0.18	0.07	0.00
SPI 3-Aug*		-2.06		-2.31
SPEI 3-Aug*		-2.11		-2.22
SPI 12-Dec*		-0.6		-1.32
SPEI 12-Dec*		-1.09		-2.1

Table 2: Monthly average temperature for Baden-Württemberg for the years 1947 and 2018. Data: 1881-2018 (138 years). (*ΔT (K)=Temperature deviation from monthly means of 1961-1990).

year	month	T_{mean} (°C)	ΔT (K)*	rank (1-138)
1947	Jan	-4.3	-3.6	125
1947	Feb	-3.9	-4.4	131
1947	Mär	4.3	+0.7	59
1947	Apr	10.1	+2.7	14
1947	Mai	14.2	+2.3	13
1947	Jun	17.5	+2.4	11
1947	Jul	19.2	+2.1	17
1947	Aug	19.2	+2.8	7
1947	Sep	16.2	+2.9	3
1947	Okt	7.9	-0.8	90
1947	Nov	5.2	+1.7	25
1947	Dez	0.7	+0.4	67

year	month	T_{mean} (°C)	ΔT (K)*	rank (1-138)
2018	Jan	4.3	+5.0	1
2018	Feb	-2.1	-2.6	116
2018	Mär	3.2	-0.4	89
2018	Apr	12.5	+5.1	1
2018	Mai	15.2	+3.3	2
2018	Jun	17.7	+2.6	8
2018	Jul	20.1	+3.0	6
2018	Aug	20	+3.6	2
2018	Sep	15.2	+1.9	16
2018	Okt	10.3	+1.6	16
2018	Nov	4.9	+1.4	31
2018	Dez	3.2	+2.9	12

(*) compared to 1961-1990

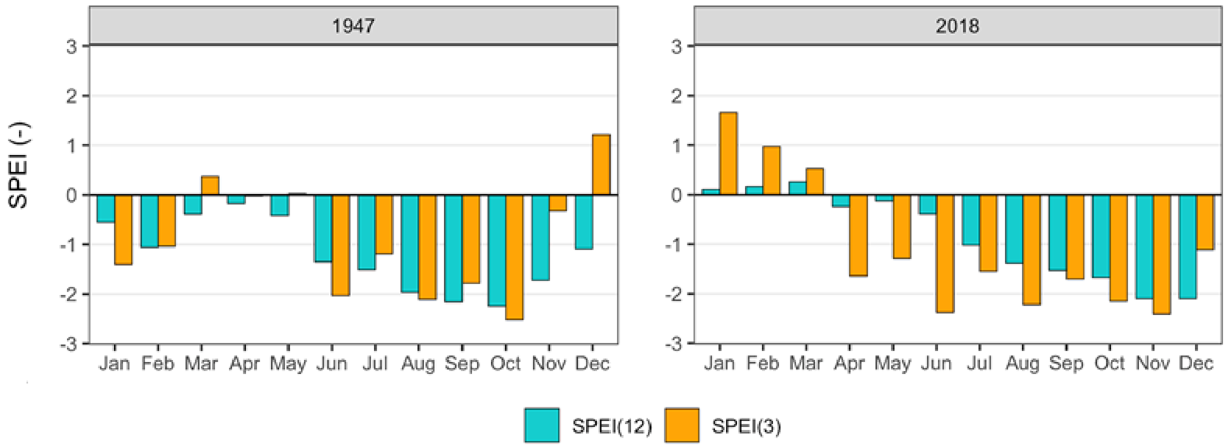

Fig 2: Comparison of SPEI-3 and SPEI-12 for the years 1947 and 2018 (data source: DWD, reference period: 1881-2018).

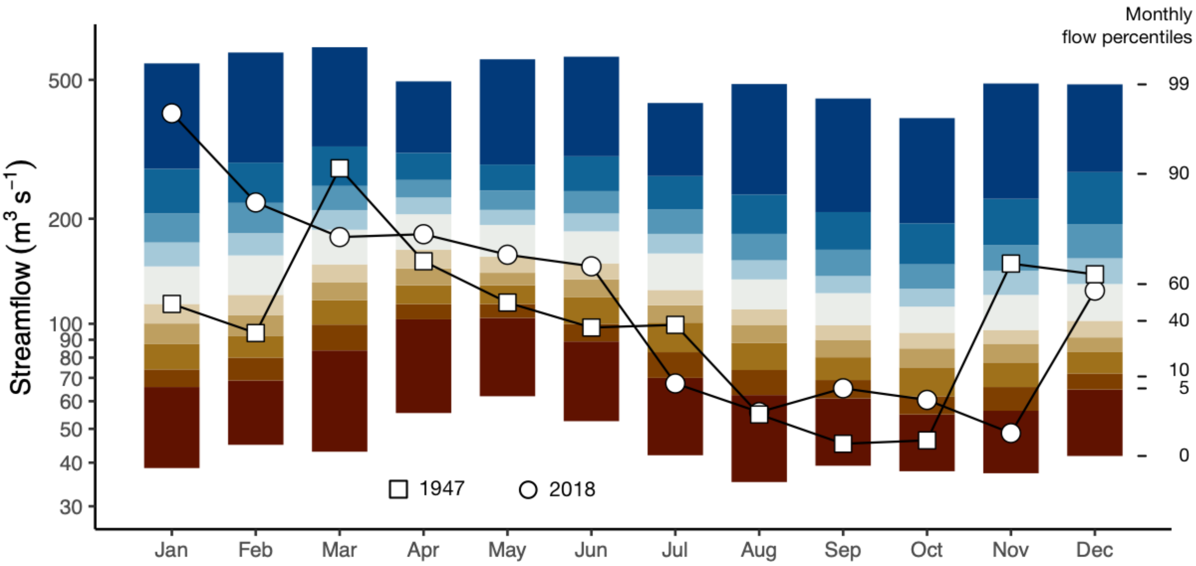

Fig. 3: Monthly streamflow at the gauge Dillingen, Danube river for the years 1947 and 2018. Colored bars show monthly flow percentiles with high flows in blue and low flows in brown. Data: daily streamflow 1924-2018.

Event comparison in respect to exposure

Between the two drought events, the total population and also the population density increased. With the increase in the installation of water closets, washing machines, and bathtubs in the 1950s, the water demand increased. Nevertheless, in 1947 the population was more vulnerable to the drought. During the drought in 1947 especially cities were exposure hotspots. Cities were more affected by a food supply crisis than rural areas, where farmers had enough food for themselves (Landesarchivverwaltung Rheinland-Pfalz 1947, 1948).

In comparison to 2018, in 1947 the drinking water supply system was an exposure hotspot to drought because of a partially destroyed or not yet developed system (Heyn 1981; Erfurt et al., 2019). In 2018, even with higher water demand, people were not exposed to drinking water supply shortages.

Event comparison in respect to vulnerability

In 2018 several monitoring systems exist, e.g. since 2005, a heat warning system was put in place, managed by the German Weather Service (DWD 2019). Also precipitation (DWD 2019), soil moisture (UFZ 2019), and low flow (BfG, HVZ) are monitored by public management organizations. In 1947 the vulnerability to natural hazards was high. The population was suffering due to the previous extremely cold winter of 1946/47 (Erfurt et al., 2019). In addition, Germany was still dealing with the consequences of the Second World War. Especially the lack of agricultural machinery and fertilizers led to losses in agriculture and food supply (Deutscher Wetterdienst in der US-Zone 1947). Nowadays, in the case of a natural disaster on a national scale (like in the case of the drought 2018), the federal government of Germany can provide financial assistance for forestry and agriculture. Private insurances (yield guarantee insurances and damage-based insurances) exist for agriculture and forestry (BMEL, 2017).

Summary

Social vulnerability towards drought events has changed in southwestern Germany since 1947. In 1947, the coping capacities were low. Especially the city inhabitants had to struggle with hunger and food shortages. In 2018 no lack of food occurred. Crop damages were compensated by the global market. Also in the water supply sector vulnerabilities were higher in 1947. In 2018, reductions in vulnerability were achieved by an extended water supply system. Water shortages were quickly compensated. The drought of 2018 strongly affected the transport industry. The monetary damage to businesses was high after both events, but in 2018 a governmental program existed to support companies whose existence was threatened by the consequences of the 2018 drought. These results provide important insights into the different aspects of a drought event. Even if the drought events are comparable in their hazards, their effects on the population were different.

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Appendix

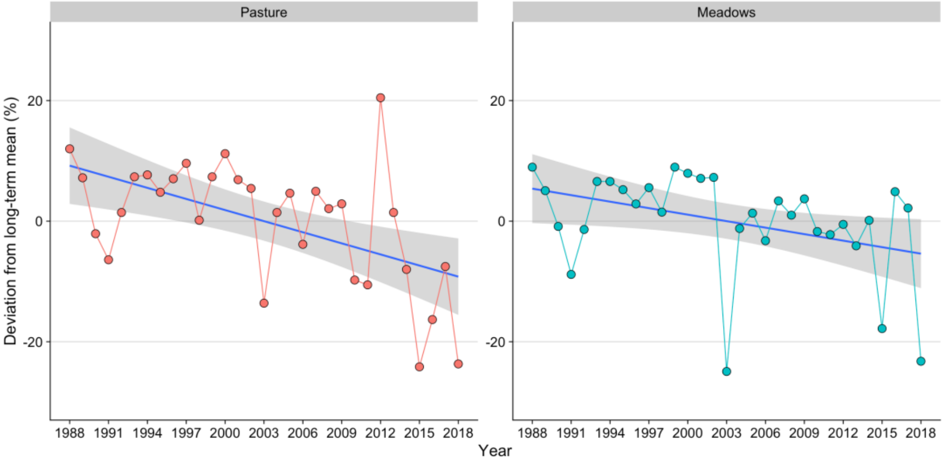

Fig. A1: Yield crops in Baden-Württemberg since 1988. Pastures and Meadows are often non-irrigated and hence a good indicator of crop losses due to drought (yearly data: 1988-2018; source: https://www.statistik-bw.de/Landwirtschaft/Ernte).

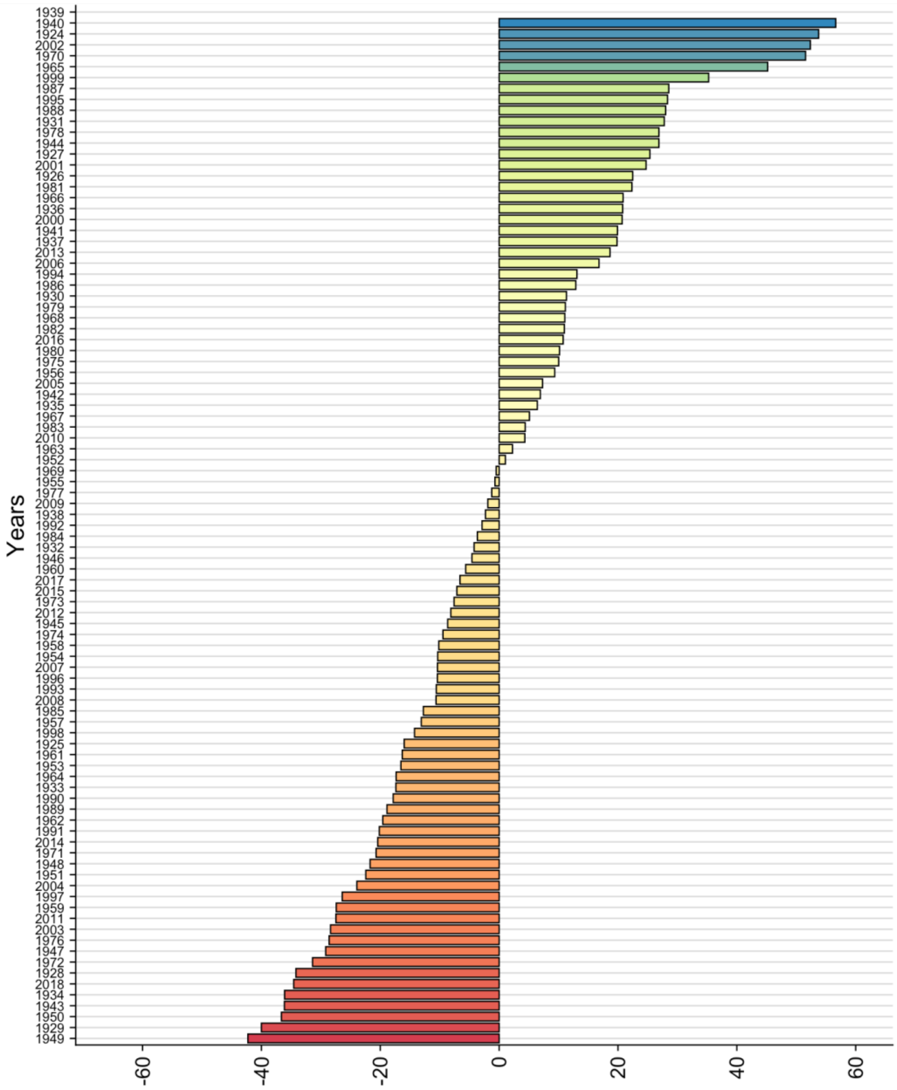

Fig. A2: Deviation from the long-term average streamflow during Mar-Nov. (in %) for Danube river at gauge Dillingen. Streamflow data time range: 1924--2018.

ID 9

Paired drought events: 2003 and 2015 droughts in Europe

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Short description of both events with a focus on impacts

The global warming is already documented by increasing of temperature anomalies in the last century and exemplified by numerous climatic extreme events which have taken place over the last decade in many parts of the world (Coumou and Rahmstorf, 2012). Europe, for instance, has been affected by numerous extreme events (Della-Marta et al., 2007; Meehl and Tebaldi, 2004; Twardosz and Kossowska-Cezak, 2013), in particular by heat waves and droughts in the last years. The heat wave and drought event of summer 2003 caused the hottest summer in the last five centuries and affected all Europe (Beniston and Stephenson, 2004; Rebetez et al., 2006), while the 2015 summer was the hottest and driest summer since 1950 in Europe (Ionita et al., 2017). During the last decades several low flow periods, at European level, occurred with severe impacts not only on the rivers themselves but also, on the civil society. The 2003 and 2015 low flow periods affected navigation, hydropower production and the environment, resulting in several types of problems to society, e.g. lack of water for drinking water supply, irrigation, industrial use and power production, hindrance to navigation and deterioration of water quality. Moreover, there were restriction/disruption of industrial production process, sport/recreation facilities were also affected by a lack of water, significant fish fatalities and stress on other aquatic fauna were recorded and tourists had to be evacuated from recreation sites endangered by wildfires, while major wildfires destroyed thousands hectares of forest, reducing tree growth and vitality corroborated with reduced productivity of annual crop cultivation.

Descriptions of processes between events with a focus on risk management

Drought events imply a series of risks to the environment and socio-human activities, because the way they are managed directly influences the final drought's costs. The preparation and implementation of Drought Management Plans should be linked to an agreed conceptual framework for drought management based on reactive and proactive approaches (Vogt et al., 2018). The reactive approach refers to crisis management and includes emergency measures and actions during the drought events trying to reduce the most dramatic and immediate drought effects by mitigating the socio-economic impacts for the moment. During the 2003 drought event, proper management and awareness tools were missing, nevertheless, during the drought events some governmental measures were taken to mitigate the drought effects: limitations in the water supply to households in rural areas and water supplementation with tank trucks delivered by firefighters or by a cistern wagon where was needed to solve problems with drinking water quality; restriction/disruption of industrial production process, limitation of the thermal and nuclear power plants, due to a lack of cooling water and/or environmental legislation for discharges into streams (Romania, Neverlands, France, Germany, Italy), closed

stream for navigation; evacuation of tourists and local habitants from sites endangered by wildfires (France, Spain). After the 2003 drought wave, the management -policy aspects have undergone major reforms in governments, including the introduction of decoupled farm payments and compulsory cross-compliance since 2003. During the 2015 drought event, the reactive approaches were similar to those taken in 2003, but better management and widespread actions at European scale led to better mitigation of socio-economic impacts compared to the 2003 drought event (Van Lanen et al., 2016; EDC, 2003a).
The proactive approach refers more to the drought risk management designed in advance according to a planning tools, which includes measures on both short-term as well as on long-term. The proactive approach entails the planning of necessary measures to prevent or minimize drought impacts in advance, with the emphasis on drought preparedness, mitigation, and response (Vogt et al., 2018). Increasing of droughts intensity and frequency in the last decades led to the awareness of the risk and vulnerability and therefore important efforts and progress have been made at European level in term of proactive approaches: drought policy instruments, research projects, and droughts management plans. For example, in 2000 was adopted the Water Framework Directive (WFD), where the drought impact and mitigation were succinctly dealt with (Hervás-Gámez and Delgado-Ramos, 2019), implementation of a Heat Health Warning System (HHWS) and its utilization by most of the European countries after the 2003 drought event (Lass et al., 2011), development of the EuroHEAT web-based forecasting (EuroHEAT, 2019), and developing the media announcements tools. After the 2003 drought event, the drought policy was revised making significant efforts for better planning regarding the adaptation and mitigation to such events. The key risk management was set by the EC Communication in 2007 by "Addressing the Challenge of Water Scarcity and Droughts in the European Union" and the publication of the technical guidance "Drought Management Plan Report Including Agricultural, Drought Indicators and Climate Change Aspects" (EC 2007). These measures led to a better management of the 2015 drought event compared to 2003, reducing the number of casualties and socio-economic loses (Van Lanen et al., 2016).

Event comparison in respect to drought hazard

The most relevant feature of both events was the occurrence of a long-lasting high-pressure system over the central part of Europe, throughout the summer months, which in turn triggered exacerbated temperatures and long-lasting periods with rainfall deficit. The European summer of 2003 was characterized by highly anomalous meteorological conditions, and was extremely hot and dry, the surface temperature anomalies associated with the heat wave being more than 5 standard deviations above the mean in some parts of Europe (Schär et al., 2003). From February 2003, a high-pressure system developed over Western Europe, blocking moist western air masses and allowing the supply of warm, dry air masses from North Africa. The result was a significant precipitation deficit (especially in February, March and August 2003), which led to a cumulative water balance deficit of up to 380 mm in South Europe and of 200 mm over most of France, Germany, western Czech Republic, Hungary and southern Romania (Environment Alert Bulletin 2004). This weather situation led to dryness and to long-lasting low water situations until October 2003. A long-lasting period characterized by a significant precipitation deficit combined with a heatwave extended across large parts of western, central and southern Europe, from May to September 2003, based on SPEI3 drought index (EDC, 2003a). The core of the 2003 drought event (12°W- 30°E; 35°N–55°N) recorded an extreme value of August SPEI3 = - 1.62. The 2003 European heat wave and drought had a massively negative impact on growth in European ecosystems. Agricultural crops and forests were much less productive than normal, and all ecosystems absorbed less of the greenhouse gas carbon dioxide from the atmosphere, death of fish and livestock, wildfires and insect invasions (EDC, 2003a). Vegetation growth across Europe was reduced during the dry and hot summer in an unprecedented way, by about 30 % (Ciais et al., 2005).

The daily discharge in central Europe largest rivers (e.g. Rhine, Elbe, Danube, Weser) dropped as early as March/April 2003, but the long-term mean low-flow discharge (MNQ) was not fallen short of until beginning of June 2003 (Figure 1a and Figure 1b). Due to the heat wave recorded in August 2003, the water level in the Rhine fell to very low levels (e.g. 65 cm in Koblenz on 15 August 2003). The lowest Rhine discharge in the Netherlands (Lobith gauge) in 2003 was very similar to that of 1976 (around 800 m^3/s) and also led to serious problems, although a total of three periods of low water occurred in 1976 with a longer overall low-water duration. Summer standardized precipitation–evaporation anomaly over a 3-month accumulation period (SPEI3) values dropped to as low as -4 in western and central part Europe (Figure 1c).
The drought conditions were recorded from late May to early September 2015, over large regions in Europe, based on the SPEI3 drought index (Ionita et al., 2017). In France, Benelux, western Germany, northern Italy, northern Spain, the Czech Republic, Poland, Ukraine and Belarus the rainfall deficit was greater than 100-130 mm, representing a reduction of about 50-60%, and in some cases even 80%, compared to the long-term average (EDO, 2015). The summer (June – August) of 2015 was characterized by daily maximum temperatures 2 °C higher than the seasonal mean over most of western Europe, and more than 3 °C higher in central Europe (Ionita et al., 2017; Van Lanen et al., 2016). The core of the 2015 drought event (0°E- 45°E; 40°N–60°N) recorded an extreme value of August SPEI3 = - 1.18.
Similar to the extreme 2003 summer drought, the large-scale atmospheric circulation over the European continent was characterized by a large, positive 500-hPa geopotential height anomaly. Positive anomalies first occurred in March, and persisted throughout the summer. This high-pressure blocking pattern over Europe prevented the flow of moisture and precipitation across much of Europe. For the 2015 European event, drought impacts are largely connected to soil water drought (crop yield, wildfires) or to hydrological drought (water supply, energy, transportation, recreation, water quality) rather than directly to the meteorological drought. Summer 2015 was characterized by extreme low flows, especially over the central and eastern part of Europe. The low flows started to develop in June (Figure 1c and Figure 1d) and they reached the lowest values in August and September. Particularly, in central Europe (e.g. southern part of Germany, Austria, and Czech Republic) the return period of the 7-day minimum flow was higher than 50 years (Laaha et al., 2017; Van Lanen et al., 2016). For the main rivers in Germany (e.g. Elbe, Danube, Rhine) the low flow periods extended over more than 3 consecutive months (Figure 1d and Figure 1e). Large parts of Europe also experienced a severe lack of rainfall and higher evapotranspiration than normal, with negative values of the three-month SPEI index (SPEI3) from June onwards across a widespread area, for example almost 75% of the area of Germany was under at least moderate drought in July 2015 (Ionita et al., 2017). Summer SPEI3 values dropped to as low as -4 in central and eastern Europe (Figure 1e). Some recovery was seen in November, but the low flows were still extreme. The hydrological drought in summer 2015 had a strong impact on different sectors like water supply, energy production, inland waterways, fisheries, tourism and recreation, agriculture and water quality (Van Lanen et al., 2016). Overall, the extreme temperatures and the drought, in summer 2003 were, amplified by a severe soil-moisture deficit (Schär et al., 2004), as a consequence of a very dry and cold winter and a very dry and warm spring. In contrast to 2003, the drought in 2015 started to develop in late spring. The winter and spring of 2015 were normal in terms of precipitation and temperature anomalies, with small exceptions over the Iberian Peninsula.

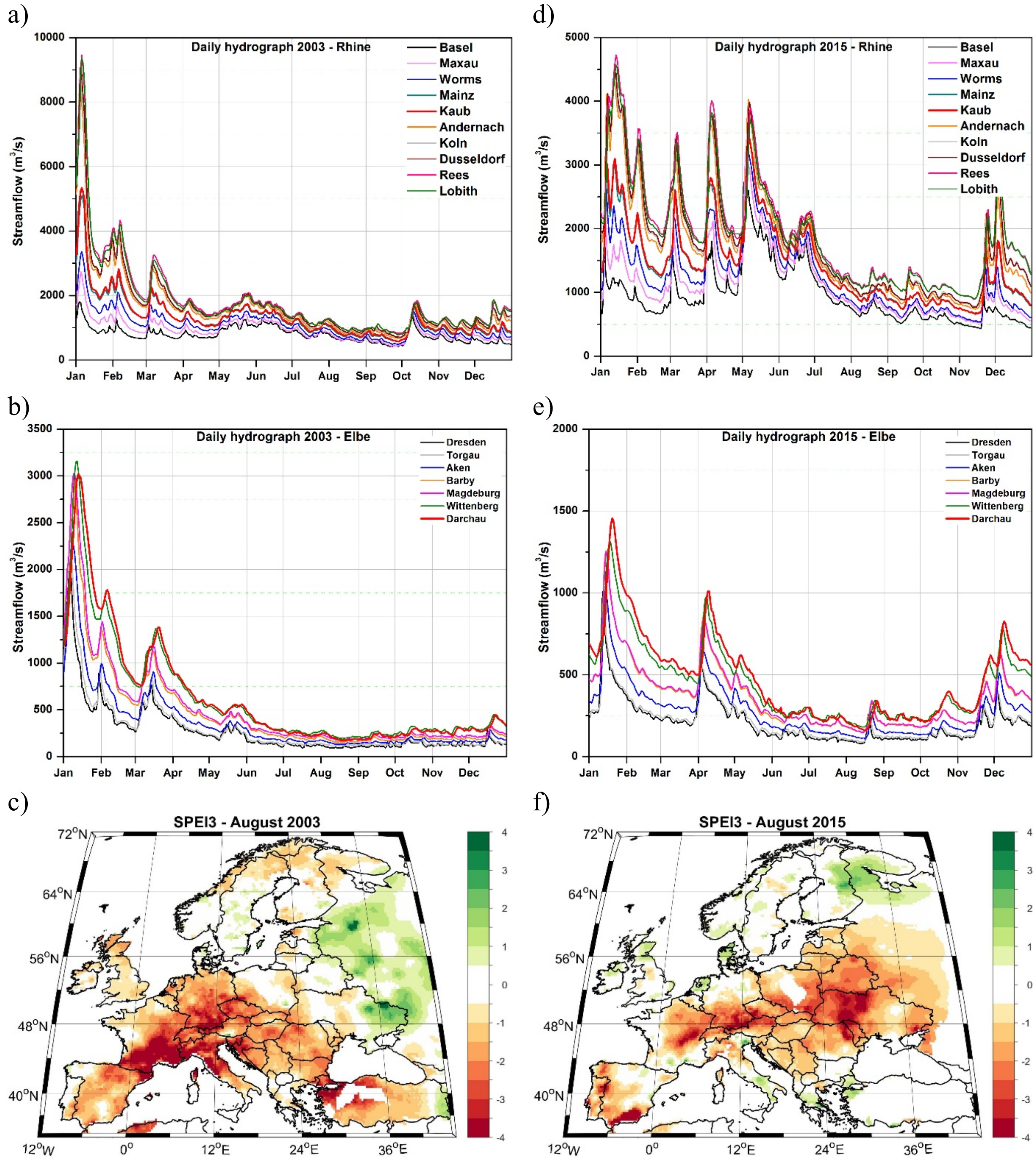

Figure 1. a) The daily hydrograph for 2003 at different gauging stations situated on the Rhine river;
b) the daily hydrogrph for 2015 at different gauging stations situated on the Elbe river; c) August 2003 Standardized Precipitation Evapotranspiration Index for a 3-months accumulation period (SPEI3) and d) the daily hydrogrph for 2015 at different gauging stations situated on the Rhine river; b) the daily hydrogrph for 2015 at different gauging stations situated on the Elbe river; c) August 2015 Standardized Precipitation Evapotranspiration Index for a 3-months accumulation period (SPEI3)

Event comparison in respect to exposure

In 2003, one-third of the European territory (3 700 000 km^2), including the northwestern parts of Spain, France, Italy, Germany, Switzerland and Austria, and the western part of the Czech Republic, was affected by the drought with different magnitudes (Rebetez et al., 2006). About 100 million people were affected by the consequences of the extreme 2003 summer drought (EU, 2010), while the associated heat wave has killed more than ~70.000 people (Robine et al., 2008). In terms of spatial extent, the European drought of 2003 affected an area spreading from Portugal to Romania and Bulgaria (Demuth, 2009; EEA, 2010), while the most affected areas were central France and eastern Austria (Laaha et al., 2017). The extended 2003 heat wave conditions were determined by diverse and far reaching effects resulting from an exceptional rainfall deficit combined with exceptional air temperature, with monthly anomalies of up to 6 ^{o}C and extreme maximum temperatures of 35 to 40°C in a large part of Europe (Rebetez et al., 2006; EurAqua, 2004; Environment Alert Bulletin 2004; DWD,2015 ZAMG, 2015). Agriculture was particularly affected in Southern and Central Europe (e.g. France, Italy, Germany, Austria, Swiss, Slovakia, Spain and Portugal), but also Eastern countries have been among the most affected by the drought and the heat wave in 2003 (COPA-COGECA, 2003; Swiss Re, 2004). In many countries of the South-Eastern European region, like Hungary, Slovenia, Croatia, Serbia and Montenegro 2003 was among the major agricultural droughts in recent years (AUA, 2011). Freshwater ecosystems were put under exceptional stress, with increased risk to biodiversity loss during 2003 (EurAqua, 2004). Reports on dried up stream sections, extreme water temperatures, violation of minimum flow requirements, dried up springs and boreholes, extremely low groundwater levels, temporary water quality deterioration and eutrophication, limited to critical dissolved oxygen concentrations, increased pollution loads, increased mortality and mass kill of fish were widespread (e.g., Massarutto et al., 2013; ICPR, 2004; Lange, 2009; EC, 2007).

In 2015, the drought conditions affected all Europe. The drought event started to develop in May 2015 over the Iberian Peninsula, in June 2015 it expanded towards France and Germany, in July 2015 the core of the drought event was over the central and southern part of Europe and in August it was extending up to Romania and Ukraine, affecting ~5 400 000 km^2 (Ionita et al., 2017). During the 2015 summer were register four heat wave episodes defined as the daily maximum temperature (Tx)>25°C, while the most affected areas were the central and eastern part of Europe and the northern Balkans (Laaha et al., 2017). In some central and eastern European regions, the impacts continued even into 2016. The climatic characteristics of the 2015 drought were similar with thus from 2003, in general lack of precipitation and maximum daily temperatures consistently above 30°C for durations of 30 to 35 days (DG Environment – European Commission, 2007), over the large parts of Europe. These conditions have a huge impact on the social and economic sectors. For example, crop losses of up to 50% were reported in the Czech Republic, Germany, Poland and Slovakia for sugar beet and potatoes, while maize was unable to build cobs in some regions (EDC, 2003). The drought also had a significant impact on livestock farming, with a 50% lower hay harvest (Czech Republic), failing grass cuts (Germany, Slovakia) and substantially lower milk production (Slovakia and Romania). The drought also led to more than 25 000 fires in Portugal, Spain, Italy, France, Austria, Finland, Denmark and Ireland, destroyed 647 069 hectares of forest areas in 2003 (Environment Alert Bulletin 2004) and 227.410 *1000 ha in 2015 (EEA, 2019b). In Austria the drought caused an exceptionally long wildfire season, lasting until the end of 2015. While sectors such as tourism, viticulture and solar energy benefited from the unusual drought conditions, many environmental and production sectors suffered due to water restrictions, agricultural losses, disruptions to inland water transport, increased wildfires, and threats to forestry, energy production, and human health. For months, the inland navigation was heavily impaired by extreme low flows and water levels of most large rivers, in 2003 and 2015. The low flows affected rivers like the Elbe or the Oder, where navigation sometimes even ceased completely, but in particular the major European transport routes of the Danube and Rhine basins (EurAqua, 2004; EC/CCR, 2005; Jonkeren et al., 2007; AUA, 2011; Massarutto et al., 2013).

Event comparison in respect to vulnerability

The 2003 and 2015 drought affected economic sectors, the environment and society, leaving a variety of impacts in its wake. The overall impact of drought in a specific area is almost always negative; in exceptional cases, some consequences of droughts such as long periods of no rain and high temperatures might be seen as positive (e.g. in tourism and open-air activities, viticulture, and solar energy production (EDO 2015)). Early warnings regarding the heat wave and the drought conditions were issued by the national administrators during both drought events (2003 and 2015). Moreover, in 2015 the awareness, preparedness, and mitigation were much better compared to the 2003 event, due to the implementation of the technical guidance “Drought Management Plan Report Including Agricultural, Drought Indicators and Climate Change Aspects” (EC 2007) and the adaptation of the EC Communication in 2007 “Addressing the Challenge of Water Scarcity and Droughts in the European Union”. These measures led to increased awareness and preparedness for the 2015 event and better adaptation measures, compared to 2003, and thus the number of casualties, social and economic losses was reduced. The 2003 event served as a starting point for better planning regarding the adaptation and mitigation to such events (Van Lanen et al. 2016).

According to COPA-COGECA (2003), European livestock farmers were worst hit due to the big impact on green fodder supply. Agricultural losses were estimated to amount to more than 10 billion Euros (COPA-COGECA, 2003, Swiss Re, 2004). Governmental measures to mitigate the effects for the farmers were taken in several countries and also by the European Commission. In 2003 the energy sector was challenged by a reduced potential of hydropower production, widespread problems with cooling of nuclear and thermal power plants as well as unusually high demands. Thermal and nuclear power plants throughout Europe had to operate at reduced capacities or even shut down due to the high river water temperatures. In August 2003 emergency exemptions from environmental legislation were granted for several power plants in France, the Netherlands and Germany in order to ensure security of supply (avoid disruptions). The situations of power supply in Italy (Cassardo et al. 2007; IReR, 2007) and France (e.g., EC, 2007; Environment Alert Bulletin 2004; Poumadèreet al. 2005) were probably the most stressed ones. A series of vulnerabilities were revealed when the National French Electricity supplier (EDF) during the heat wave episode requested temporary exemptions for one third of its nuclear park (Poumadère et al. 2005). Already at the beginning of June there were some unexpected (sometimes long-lasting) blackouts in Italy, due to the increase of electric energy demand above the threshold of productivity, which caused several inconveniences and knock-on losses in industrial activities, e.g. steel production (Cassardo et al., 2007; IReR, 2007). Overall, the 2003 event caused significantly more economical and societal damages, compared with the 2015 event. According to eea.europa.eu data, the economic damage due to climatological events in Europe in 2003 was 17.134 billion euro while in 2015 was 2.172 billion euro (EEA, 2019a). This can be partially attributed to the large spatial extent of the summer 2003 event, as well as the publication of the Drought Management Plan by the EC Communication in 2007 which contributed to a better adaptation and mitigation plans in 2015 (EC 2007, Hervás-Gámez and Delgado-Ramos, 2019). For instance, in the Czech Republic, reservoirs were 90% full at the start of the 2015 summer. During the drought event, reservoirs were emptied to provide direct water and to increase low flows downstream. Reservoir storage remained above 30% with a few exceptions, but most reservoirs were still in decline at the end of October 2015, which had not happened since 2003. In many regions of Europe, the decision was made to irrigated the crops, to limit or even to complete cessation of inland water transportation, to restrict civil and industrial water uses, to initiate the construction of additional (large scale) water supply networks. Various measures were also taken for human health and public safety reasons. In German, Dutch, Slovak and Romanian cities, additional water was required for watering parks to avoid further development of the urban heat island and to maintain aesthetic value. In Bratislava and Bucharest, water tanks were used to supply tourists and city inhabitants at selected points (Van Lanen et al., 2016).

Both events affected agricultural production heavily (e.g. arable crops and animal feed) in many EU countries. At the request of many member states, the European Commission has activated a number of measures and derogations**.** Nevertheless, depending on where they are located on the EU territory, European farmers have faced more or less support from the national public authorities**,** each managing the crisis depending, of course, on its intensity, but, also and above all, depending on its financial capacity, exposing each farmer to significant disparities in treatment. Austria, Bosnia and Herzegovina, Czech Republic, Croatia, Hungary, Serbia, the Slovak Republic and Moldova reported high impacts on agriculture. In areas with periodical irrigation, such as the Marchfeld region in Austria, water demand was significantly above the long-term average due to precipitation deficits starting with March/April and continuing in June/July 2015. The most significant impact was on corn production (Austria, Croatia, Serbia, Slovak Republic) (ICPDR 2017). In 2003 the fodder deficit was up to 60 % (France), the maize up to 30% (Italy), wheat up to 20% (France and Austria), and potatoes deficit was 25 ‰ in Italy and France, while the in 2015 the crop losses was up to 50 % in Czech Republic, Germany, Poland and Slovakia (Environment Alert Bulletin 2004, ICPDR 2017). While in 2015 was register with a 50% lower hay harvest (Czech Republic, Germany, Poland and Slovakia), failing grass cuts (Germany, Slovakia) and substantially lower milk production (Slovakia and Romania) (Van Lanen et al., 2016).

Summary

The heat wave and drought event of summer 2003 caused the hottest summer in the last five centuries and affected all Europe (Beniston and Stephenson, 2004; Rebetez et al., 2006), while the 2015 summer was the hottest and driest summer since 1950 in Europe (Ionita et al., 2017). The 2003 and 2015 droughts events had a high impact on the economic, socio-economic, industrial productivity, environment, agriculture, public, surface and ground-water, and tourism and reactivation domains. Overall, the 2003 and 2015 low flow periods affected navigation, hydropower production and the environment, resulting in several types of problems to society, e.g. lack of water for drinking water supply, irrigation, industrial use and power production, hindrance to navigation and deterioration of water quality, restriction/disruption of industrial production process, sport/recreation facilities affected by a lack of water, tourists had to be evacuated from recreation sites endangered by wildfires, major wildfires destroyed thousands hectares of forest, reduced tree growth and vitality, fish fatalities and stress on other aquatic fauna, reduced productivity of annual crop cultivation.

Still, these two events are different from the exposed area, crisis management, impact, and total costs point of view. The 2003 drought event affected a large part of the central Europe, including the northwestern parts of Spain, France, Italy, Germany, Switzerland and Austria, and the western part of the Czech Republic. The superficial treatment of the drought impact and mitigation in the WFD, and the lack of concrete management plans of action during the 2003 drought event led to 70.000 deaths and 17.134 billion Euro of direct impact (EEA, 2019a). The 2015 drought event affected mostly the central and eastern part of Europe and it was the hottest and climatologically driest summer over the 1950–2015 study period for an area stretching from the eastern Czech Republic to Ukraine (Ionita et al., 2017). The socio-economic impact in 2015 (~1250 deaths and 2.172 billion euro of direct impact (EEA, 2019a)) was much lower compared to the 2003 event, due to the awareness of the risk and vulnerability of the drought events which led to adaptation of the EC Communication in 2007 "Addressing the Challenge of Water Scarcity and Droughts in the European Union" and the publication of the technical guidance "Drought Management Plan Report Including Agricultural, Drought Indicators and Climate Change Aspects" (EC 2007).

Unlike floods, for which a specific Directive was adopted in 2007, droughts are not yet the subject of EU law. However, increasing drought trends in multiple EU regions over the last decades have led the European Commission, Member States, scientists and stakeholders to reflect upon specific measures that should be taken to better manage drought risks and impacts. This is particularly reflected by the 'Water Scarcity and Drought 'Communication (European Commission, 2007b) and by the 'Blueprint to Safeguard Europe's Water Resources' (European Commission, 2012). The impacts produced by droughts are numerous. Water supply to populations may be affected, irrigated crops can have severe restrictions and river ecosystems may suffer the consequences of low river flows, among other problems. The duration and related impacts of droughts can greatly vary in different countries. While in those countries lacking water storage infrastructures, where water supply is directly dependent on rainfall, a decrease in rainfall during some months can become a drought, in other countries with enough storage infrastructures, the greatest impacts occur when there are consecutive water deficits for longer periods of several years. Prolonged droughts with severe impacts, such as the major droughts in 2003 and 2015 have highlighted Europe's vulnerability to this natural hazard and alerted governments, stakeholders and operational agencies to the disastrous effects droughts may have on the society and economy, including the need for mitigation measures (Estrela et al, 2001). The EC Communication from 2007 and the national administration's plans have contributed to a much better preparation and mitigation of the 2015 drought event compared to 2003, thus the reduced number of casualties and socio-economic loses in 2015 (Van Lanen et al., 2016).

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ID 10

Paired hydrological drought events:1991-1992 and 2005 droughts in the lower Limpopo catchment in Mozambique

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Short description of both events with a focus on impacts

Limpopo River basin is one of the most water stressed basins in Africa, and is exposed to both droughts and floods. Lower Limpopo River Basin in Mozambique experienced a hydrological drought in 1991-1992, which affected about 3.3 million people and resulted in large economic damages [1]. This event is here compared with a hydrological drought in 2005, which affected approximately 1.4 million people [1].

Descriptions of processes between events with a focus on risk management

The estimated water use by the countries within Limpopo River basin is 60% for South Africa, 30% for Zimbabwe, 6% for Mozambique and 4% for Botswana [2]. Over time, the drought effects in lower Limpopo have been exacerbated by increased water withdrawals from a large number of reservoirs located upstream [3]. The flow entering Mozambique has been reduced, and the river is now dry for 3-4 months per year, but can fall dry up to 8 months in a year [4]. The total water use in the Mozambican part of the Limpopo River is 283 Mm3/year, whereof irrigation is the largest sector of water use by 270 Mm3/year [2]. Irrigation is concentrated in Chokwé and Xai-Xai.

Mozambique has two dams within the Limpopo River basin. The Massingir dam, located on a tributary of the Limpopo, 30 km downstream of the South African border, has a storage capacity of 2800 Mm3 and was designed as a multi-purpose irrigation and hydro-power dam, as well as storage of water and flood protection. However, the dam has so far not fulfilled its potential. A serious leak was discovered in 1978 after the first impounding. It was later rehabilitated during 2003-2006, but a breach of the bottom flood gates occurred in 2008 and it was, in 2009, estimated to take two or more years to repair [5]. The Maccaretane weir has a small storage capacity of 4 Mm3, which dams the Limpopo River to maintain water level of the Chokwé irrigation system, but releases water when flows are greater than 2500 m3/s [5].

The water sector in Mozambique was centralized until 1991, when decentralisation began with the Water Law. However, there have been major constraints in the decentralisation process due to weak institutional capacity, and as of 2009, only the Southern Regional Water Administration (ARA-Sul), who is responsible for lower Limpopo, is fully operational [5]. The policy development in Mozambique has been largely government-driven, where the National Directorate for Water (DNA) manages the water resources and gives guidance to the regional water authorities, e.g., ARA-Sul.

Lower Limpopo River basin in Mozambique suffers from two hydrological extremes, droughts and floods, and thus has to plan for both hazards. The drought in 1991-1992 was exacerbated by ongoing warfare and political-economic instability from the civil war that ended in 1992 [6]. Over the 13 years between the two events (1991-1992 and 2005), the area has experienced a smaller drought in 2002-2003 and a catastrophic flooding event in 2000.

Population in Mozambique has continued to increase with 53% between 1992 and 2005, and today the majority of the population (66%) lives and works in rural areas [7]. As a response to the frequent droughts, Mozambique has changed some of the traditional cropping patterns. For example, millet and sorghum, which are more drought tolerant, have started to replace maize, a more sensitive crop, in low rainfall areas [8].

To cope with recurring natural hazards, the Mozambican government created the Department for the Prevention and Response to Natural Disasters (DPCCN) in 1980 to take responsibility for providing humanitarian assistance and overall coordination in disaster response [9]. The DPCCN was restructured in 1999 and renamed the National Disaster Management Institute (INGC). INGC was then scaled down to plan and coordinate emergency prevention and response [9]. The Government of Mozambique acknowledge that the impacts of and response to disasters such as droughts are related to the overall development of the country. As a response to this challenge, the United Nations Development Programme (UNDP) and its partners are implementing the Coping with Drought and Climate Change (CwDCC) project in the country. The aim of the project is to reduce vulnerability to drought in agricultural areas and train communities, e.g., to grow drought-resistant crops, and to improve communication regarding weather forecast and climate information [10].

Event comparison in respect to drought hazard

Lower Limpopo in Mozambique experienced a severe drought in 1991-1992, and another one in 2005, both events were related to the El Nino Southern Oscillation (ENSO). These events were captured by a study of Trambauer et al. [11], who analysed hydrological droughts in the Limpopo River basin in the period 1979-2010 using a finer resolution version (0.05° x 0.05°) of the continental-scale hydrological model PCRaster Global Water Balance. The results were compared with reported historic drought events during the same period. Figure 1 shows the outcome of the study for the sub-basin of Chokwé hydrological station in lower Limpopo, where hydrological drought was characterized and identified for 1991-1992 and 2005 by using the indicators Standardized Runoff Index (SRI), Standardized Precipitation Evaporation Index (SPEI) and the Standardized Precipitation Index (SPI). They also computed drought severities (DS (months)) resulting from the different indicators, where the 1991-1992 and 2005 droughts were identified as being among the most severe droughts, but the end month of these events varies for the different indicators. For example, indicators with higher aggregation periods, e.g., 12 and 24 months, used as indicator for groundwater droughts show longer droughts compared to indicators with lower aggregation periods, e.g., 3 months for agricultural drought. This is illustrated in Figure 2 with Chokwé sub-basin as an example.

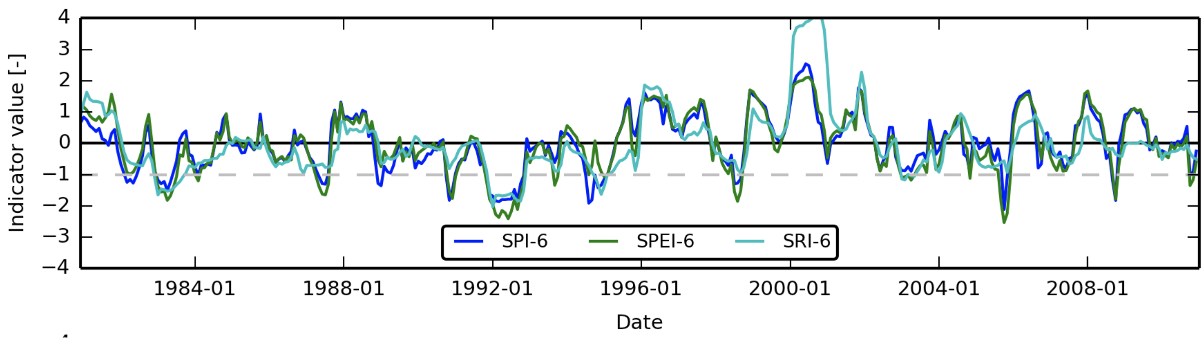

Figure 1. Time series of aggregated drought indicators for Chokwe sub-basin with indicators used to characterize hydrological drought (SPI-6, SPEI-6 and SRI-6). The dotted grey line at the threshold value of -1 is used to identify moderate droughts, with the moderate drought

considered to start when the indicator falls below the threshold, and stop when the indicator goes above the threshold (Figure from Trambauer et al. [11]).

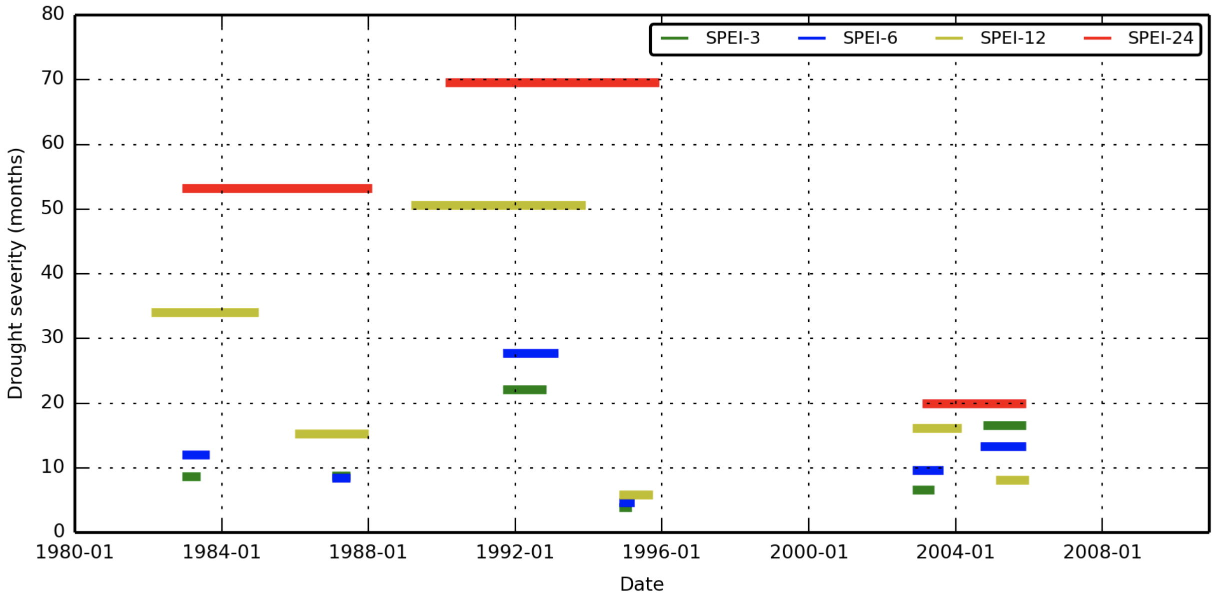

Figure 2. Drought severity and duration in Chokwe sub-basin for the six most severe droughts in the period 1980-2010 for the indicator SPEI with different aggregation periods to represent agricultural (SPEI-3), hydrological (SPEI-6, SPEI-12) and extended hydrological droughts (SPEI-24, multi-year droughts) (Figure from Trambauer et al. [11]).

Event comparison in respect to exposure

The 1991-1992 drought event affected about 3.3 million people in the lower Limpopo River basin, and resulted in estimated total economic damages of 50 million USD [1]. Around 1.32 million people were directly affected, particularly the rural poor that had to seek refuge in urban areas causing accelerated population growth in urban centres of the country [12]. The impacts were exacerbated by the ongoing civil war and caused loss of food supplies, livestock and environmental degradation. Up to 1.5 million lacked food, production went down, and water shortages were reported in cities and rural areas [13]. An emergency appeal for an additional 300,000 tonnes of food was launched by the government, and the World Food Programme spent nearly 200 million USD in providing food aid relief [12]. The 1991-1992 drought affected many parts of southern Africa, which received less than 75% of their average rainfall causing up to 70% of the crops failing [14]. According to FAO [14], approximately 86 million people were affected in southern Africa (72% of the population), whereof 20 million were at serious risk of starvation.

The 2005 drought event affected over 1.4 million people, and approximately 317,000 ha of lost agricultural production resulting in 70 million USD estimated cost of losses [8]. Less than 60 mm in rainfall led to yields lower than 180 kg/ha. This resulted in, for example, the price of white maize to spike the following year (2006) [8]. In April 2005, the Government of Mozambique estimated that 180,000 families were exposed to the risk of droughts. In early June, they made an official request to the World Food Program to provide food through a Food for Work scheme to 550,000 people in need [15].

Event comparison in respect to vulnerability

The 1991-92 drought event coincided with the ongoing civil war in Mozambique, and the economic hardship in the countryside limited the government’s ability to put down rebel activity. It was not until the peace accord was signed in 1992, ending the 17-year civil war, that NGO's were able to provide emergency relief to drought-affected areas [6]. The country also experienced a cholera outbreak after the drought, due lack of adequate drinking water, with approximately 31,000 severe cases and 750 casualties reported [12]. The 2005 drought event pushed a large part of the households below the poverty line (poverty increased by 12%), due to the reduction in consumption caused by losses in agricultural production [16].

During the 1980s and 1990s, the Department of Prevention and Combat of Natural Disasters (DPCCN) was officially responsible for disaster response in Mozambique [17]. However, during the time of civil war, much of the relief operations for drought affected areas were diverted to only respond to acute emergency situations [12]. It was not until the International Decade for Natural Disaster Reduction (1990s) that risk management concepts were introduced and formalized. DPCCN was then transformed into INGC (in 1999) with focus in disaster risk management [17]. The National Institute of Disaster Management (INGC) is responsible for the coordination of disaster preparedness and response in the country, while the National Institute of Meteorology (INAM) is responsible for monitoring and disseminating warnings and alerts for extreme weather and climate events [18]. Although there is national EWS for weather related hazards, there has been a lack of an early warning system for droughts at a district level. Instead, local communities relied on traditional knowledge by using natural references, such as lake water levels in the beginning or middle of the rainy season, or the wind direction, e.g., frequent westerly winds may be a signal of a dry year [19].

Summary

The paired event study shows that the 1991-1992 hydrological drought was more persistent than the 2005 event (Figure 1 and 2) and affected a larger part of the population. The 1991-1992 drought also coincided with the ongoing civil war, which made the society more vulnerable to the impacts of the drought. The cholera outbreak following the drought also led to large indirect effects. Although, Mozambique was less affected during the 2005 event, both in terms of hazard and exposure, the drought effects in the lower Limpopo river basin have and will likely continue to be exacerbated due to upstream water withdrawal and the large irrigation scheme. In addition to recurring droughts, the area is also exposed to floods, which increases vulnerability to extreme events.

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ID 11

Paired flood events: groundwater floods on the Chalk outcrop of West Berkshire, UK, in the winters of 2000/01 and 2013/14

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Short description of both events with a focus on impacts

Exceptional rainfall in the UK in the autumn and winter of 2000/01 caused the most extensive fluvial flooding seen for several decades (Marsh and Dale, 2002). The substantial groundwater recharge that also occurred, compounded by above normal antecedent groundwater levels, resulted in unprecedented groundwater levels and prolonged groundwater flooding, especially in the Chalk outcrop of southern England (Figure 1 inset). The vast majority of groundwater flood incidents were observed in the upper, normally-dry valleys on the dip slope of the Chalk escarpments. This case study focusses on West Berkshire (704 km^2), a large proportion of which (62%) is underlain by the outcrop of the Chalk aquifer (Figure 1). Here, in 2000/01 groundwater flooding was reported to have directly affected many properties. Although total numbers were not reported, based on data from the 2013/14 event, it is thought this was >100 properties. In addition, problems were caused by the groundwater inundation of farmland, the surcharging of sewers and storm drains by groundwater, and the flooding and subsequent closure for days to weeks of many major and minor roads (Robinson et al, 2001; WBC, 2002).

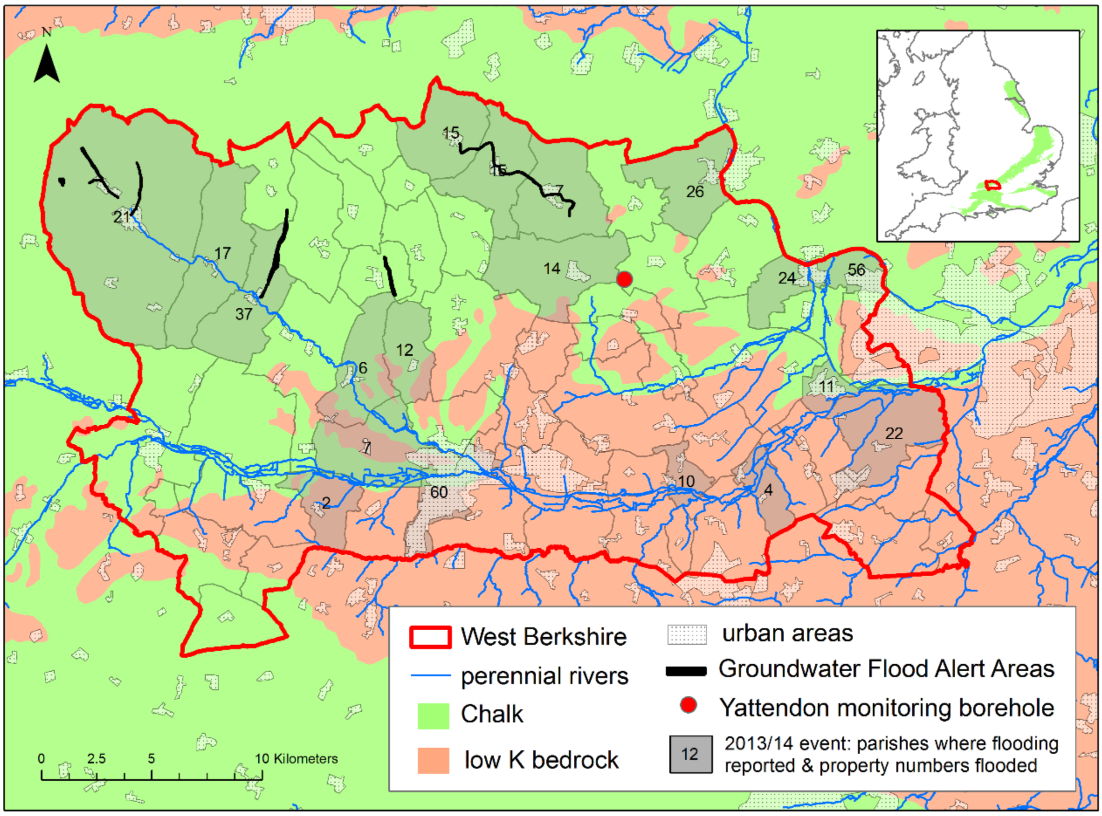

Figure 1 Chalk outcrop, river network and Groundwater Flood Alert Areas in the West Berkshire area, along with parishes flooded during the 2013/14 event and number of properties flooded in each, as reported by West Berkshire Council (WBC, 2014). BGS © UKRI 2022. All rights reserved. Contains Ordnance Survey data © Crown copyright and Environment Agency data ©.

In the winter of 2013/14, the UK had the wettest winter on record (Muchan et al, 2015). In the period December 2013 to February 2014, the West Berkshire area received over twice the long term average rainfall (Morris et al, 2018). In the autumn, groundwater levels in Chalk boreholes were in the normal range, however, as a response to the exceptional rainfall, level rises of tens of metres were recorded and by January groundwater was emerging in the normally dry valleys in the higher elevations (Morris et al, 2018). As in 2000/01 this groundwater flooding affected the villages in the higher catchment areas and lasted for many weeks (WBC, 2014). Within the West Berkshire Council (WBC) area, 366 properties were reported as having flooded (Figure 1) and it is estimated that approximately 200 of these were associated with groundwater. The types of flood receptors were the same as in 2000/01, and again there were no fatalities or serious injuries reported. The widespread flooding in 2014 revealed risks from the combined effect of high groundwater and flooding from groundwater-fed rivers in small rural communities in the WBC area, and the problem of flooding in urban areas from groundwater infiltration into foul sewers, and the associated public health issues. The local water company, Thames Water, reported substantial costs in tankering effluent that had to be pumped from the sewerage network due to the effects on the system of the ingress of large volumes of groundwater. During the period of the flooding 20 road closures or restrictions were reported in the WBC area, lasting days to weeks (Ascott et al, 2017).

Descriptions of processes between events with a focus on risk management

The protracted and widespread flooding experienced across much of the UK during the winter of 2000/01, led to a flood risk management review commissioned by the UK Government. It was recognised that there was a lack of understanding of the groundwater flooding mechanisms that had played such a significant role in the 2000/01 floods, and in the following years a series of research studies were undertaken on this form of flooding, funded by the UK Government (Cobby et al, 2009). The major floods of the summer of 2007 led to a major review (Pitt, 2007) and wholesale changes in flood management in the UK. By 2010, national policies, including the Flood Risk Regulations 2009 (FRR 2009) and the Flood and Water Management Act 2010 (FWMA 2010), had been introduced to address the recommendations of the Pitt Review, as well as the EU Floods Directive. Responsibilities for the management of flooding from surface water, groundwater and ordinary watercourses in England were assigned to Lead Local Flood Authorities (LLFA). The relevant Government environmental regulator, the Environment Agency, retained a strategic overview role for all sources of flooding but provided guidance on groundwater flooding for the LLFAs, including detailed mapping. Under the FRR, within a six-year flood risk management cycle, there is a requirement to keep up to date information to support other local flood risk assessments, and to identify and address areas of significant flood risk.

In addition to the FRR/FWMA requirements, National Planning Policy was also introduced in the period between the flood events, that requires the adoption of proactive strategies to mitigate and adapt to climate change, including taking full account of flood risk. As required, the WBC commissioned a Strategic Flood Risk Assessment that informed Local Flood Management Plans. Works were undertaken to improve drainage to contain and convey emergent groundwater (see below). Legislation provided the framework within which local community-led groups evolved that were, and continue to be, significant drivers of action to address flooding problems.

In the period between the two flood events being compared here, advances in remote monitoring of water levels, along with the recognition of the need for an improved flood early warning, led the Environment Agency to develop a sophisticated nationwide early warning system. Although primarily addressing fluvial flooding, it also includes groundwater flooding in those areas known to be vulnerable. Two Groundwater Flood Alert Areas were delineated on the Chalk outcrop in the WBC area (Figure 1).

Event comparison in respect to pluvial flood hazard

The flooding experienced across much of the UK in 2000/01 was associated with the passage of a sequence of vigorous frontal systems bringing successive heavy pulses of rainfall (Marsh and Dale, 2002). Over the period September to December 2000, the catchment of the River Thames, within which the Chalk of West Berkshire is located, received 190% of the long term average rainfall for the period (Robinson et al, 2001). The elimination of soil moisture deficits in the autumn of 2000 meant the groundwater recharge season was longer than normal and continued late into the spring of 2001 (Marsh and Dale, 2002). In parts of the Chalk, recharge in October and November exceeded the annual mean (Robinson et al, 2001). Water tables were already above average levels at the start of the autumn following three successive winters with above-average rainfall. By November 2000, the high groundwater levels were causing exceptional flows in Chalk rivers and by December, flows were occurring in normally-dry valleys in higher catchment locations. Figure 2 shows the long-term groundwater hydrograph from a representative monitoring borehole (near the village of Yattendon – see Figure 1) in the Chalk of West Berkshire. Expert knowledge has identified a groundwater level of 78 metres above sea level (masl) in the borehole as an approximate threshold above which localised groundwater flooding occurs. In the 2000/01 event the groundwater level was above this threshold for 156 days (17 Jan - 22 Jun 2001), the longest in the record (since 1974), and also reached its highest recorded level (82.04 masl).

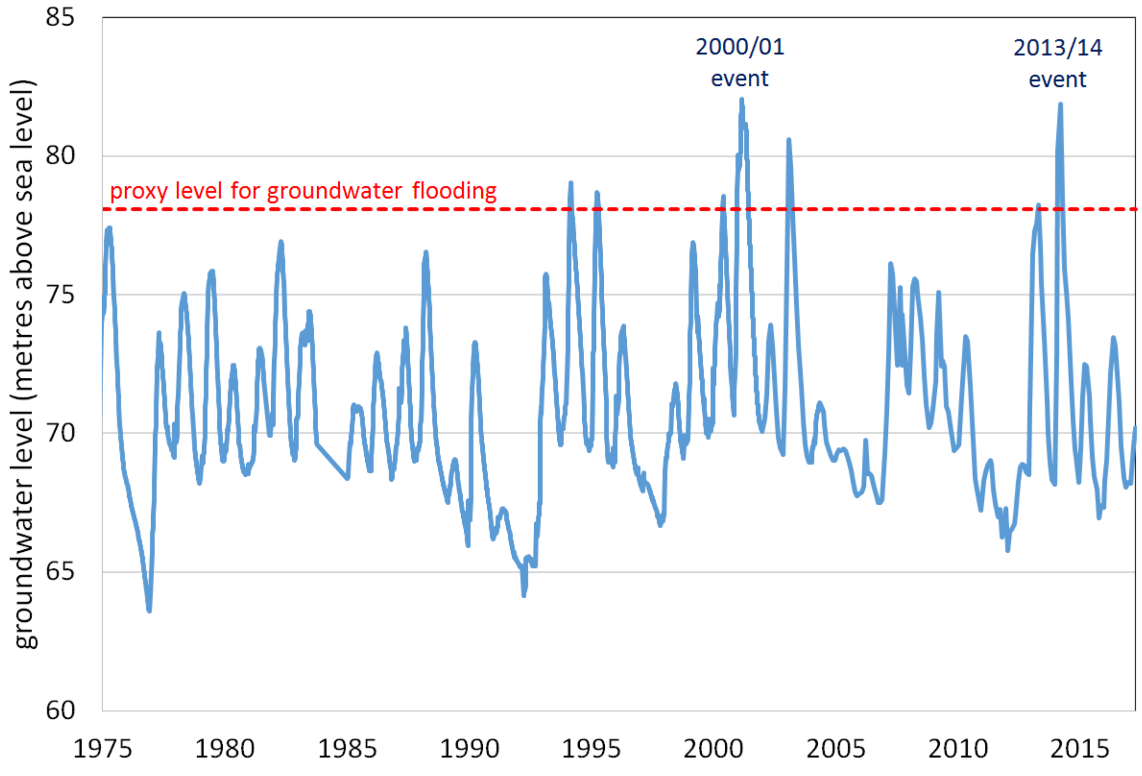

Figure 2 Groundwater level record from Yattendon monitoring borehole, showing the proxy level above which groundwater flooding is initiated in the locality. BGS © UKRI 2022. All rights reserved. Contains Environment Agency data ©.

Throughout the winter of 2013/2014, a succession of vigorous low pressure systems crossed the UK. This resulted in the wettest winter on record for the UK since records began in 1910 (Kendon and McCarthy, 2015). Major storms from December 2013 through to February 2014 resulted in exceptional river flows, including groundwater-fed streams on the outcrop of the Chalk across the southern UK. Within the WBC, a series of fluvial flooding events occurred associated with the Rivers Kennet, Lambourn and Pang. In the period December 2013 to February 2014, the Chalk of the WBC area received ~230% of the long term average rainfall for the period (Morris et al, 2018). In the autumn of 2013, groundwater levels across the country were generally in the normal range, including in Chalk boreholes in the WBC area. A month later, however, substantial rises in groundwater levels had occurred in the Chalk of southern England. In January, groundwater emerged above the ground in ephemeral streams in the WBC area and alerts were issued in the two Groundwater Flood Alert Areas (Ascott et al, 2017). In the Yattendon monitoring borehole the groundwater level was above the flooding threshold for 102 days (1 Feb – 13 May 2014), the second longest in the record, and reached the second highest recorded level (81.88 masl; note, daily data are available for 2001, whereas only monthly data are available for 2014, therefore it is probable that the peak in 2014 was higher and the period of flooding longer). A slow decline of groundwater levels into the spring of 2014 meant that in areas of WBC these alerts remained in place until late May; during this period sewers continued to surcharge, some basements were still being pumped and some minor roads remained submerged, in some cases extending into July (Ascott et al, 2017).

Event comparison in respect to exposure

Data from the UK Censuses for 2001 and 2011 help to assess the increase in population between the paired events (it is acknowledged that these data do not cover the full period between events). These data can be used as an indication of the increase in exposure to flooding although it is not possible to quantify numbers of people. The population of the WBC area in 2011 was 154,000, an increase of 6% from 2001 (less than the regional average of 8%). The Chalk outcrop underlies ~62% of West Berkshire. Settlements in most of the Chalk outcrop area are small and dispersed, however, more densely populated urbanised areas, such as Newbury, Purley-on-Thames and Theale, have also been identified as at risk from groundwater flooding (WBC, 2002; WBC, 2014). The population increase in West Berkshire was generally higher in urban areas (e.g. 11% in Newbury) and lower in the more rural areas (4%). The road network, the flooding of which had a substantial socio-economic impact during both floods, did not change significantly between the two events. Other vulnerable infrastructure, such as the sewerage network, grew commensurate with the population increase, although it is assumed the added network was constructed to be less prone to groundwater infiltration.

Event comparison in respect to vulnerability

The floods of 2000/01 were the worst that had been experienced in UK for several decades, and the first major groundwater floods that those in the local and regional authorities had had to deal with. The capacity to manage localized flooding was significantly reduced in the early 1990s subsequent to the privatisation of the water industry in the UK, as a generation of experienced engineers were lost as Local Authority Drainage Units were disbanded (Pitt, 2007). This compromised (and to some extent, still is compromising) the ability to respond to and address flood impacts.

During the period that followed the 2000/01 floods, and leading up to the 2013/14 event, there were a series of further major floods that affected the WBC area, also involving a significant component of groundwater flooding. These floods raised the awareness of the implications of flooding with local authorities, water utilities, the Environment Agency, emergency services and the general public. The flood risk assessments required by new legislation also raised awareness and ensured increased emergency planning was undertaken, and funding for flood-risk-reduction measures secured.

With each flood came measures to improve the protection of flood-prone property and infrastructure. In the WBC area, many of these measures addressed the hazards associated with groundwater flooding, including: the removal of blockages of water that caused flooding, such as the clearing of culverts; the installation of new drainage, including bypass channels around vulnerable locations, and further road culverts; the raising of key roads at vulnerable sites; and the use of pumps within the borehole network of the West Berkshire Groundwater Scheme (the purpose of which is stream augmentation during low-flow periods) to lower groundwater levels during periods of groundwater flooding (the effectiveness is not clear).

The characteristics of some of the communities at greatest risk increased their effectiveness and ability to make authorities accountable, i.e. that they are collections of villages with existing strong networks and with a high proportion of professionals that were able to define and articulate their needs well and mobilise political support (e.g. Pang Valley Flood Forum https://www.floodalleviation.uk/). They were better able to work with the authorities to access new funds available for local-scale mitigation that required evidence of effective local partnerships.

Summary

Both events were characterized by persistent groundwater flooding. Groundwater level data indicate the event in 2000/01 was more extreme, but there was less evidence of impact during this event compared with 2013/14. Both the greater awareness of flooding and the knowledge of the areas where groundwater flooding was likely to occur are thought to have increased the amount of impact data captured in the 2013/14 event. In contrast, the awareness of the implications of declaring flood damage on house value and insurance premiums may have affected the willingness of house owners to provide information during this later event.

It is likely that preparedness, through measures to reduce exposure and vulnerability and increase resilience between the two events, will have reduced the impact of the 2013/14 floods, as will early warning systems, where in place. The drive for measures came about through awareness of the impacts of flooding as a result of the numerous flood events that occurred in the period between the two events being compared, as well as a consequence of new legislation.

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Paired flood events: 21 September 1995 and 6 September 2018 pluvial floods in the Barcelona city in Spain

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Short description of both events with a focus on impacts

Barcelona (NE of the Iberian Peninsula) is one of the cities of the world with a major population density (165.9 inh./ha in a surface of 9907,4 ha in 1995 -Ajuntament de Barcelona, 1996-; 160 inh./ha in a surface of 10135.3 ha in 2018 -Ajuntament de Barcelona, 2019b). The population increase was mainly concentrated between 1960 (1.557.863 inh.) and 1980 (1,752,627 inh.), and from 1995 (1,614,571 inh.) and 2018 (1,620,343 inh.) this increase has been relatively low (Ajuntament de Barcelona, 2019a). On the contrary the touristic activity has increased enormously between 1995 and 2018 (from 34,753 to 152,056 tourism places; from 3,089,974 to 32,571,533 overnight stays -Ajuntament de Barcelona, 1996, 2019b-). To the west of the city is placed the Collserola mountain (512 m.a.s.l.) where are born all the streams that cross Barcelona city. To the south of the city it is the Llobregat River (average flow in the mouth, 19 m^3/s; length 170 km, basin surface, 4,948 km^2) and to the north the Besós River (4.33 m^3/s; 18 km; 1038.31 km^2) although, when they overflow, they mainly affect the municipalities of the south and north of the city of Barcelona, where floods are usually pluvial.

Between 1351 and 2005, 85 flash floods and pluvial floods have seriously affected the city of Barcelona (Barrera et al., 2006). Although 64 pluvial flood events have been recorded in the city between 1981 and 2010, their impact has decreased. Despite this, the "Consorcio de Compensación de Seguros" (CCS) has paid more than 7 Million $€_{2015}$ for flood damages between 1996 and 2014 (personal communication from CCS). There is some correlation (+0.56 for the period 1940-2012) between the annual total flood index and the number of days exceeding 50 mm of rain in Barcelona (Barrera-Escoda and Llasat, 2015). The analysis of the flood series of Barcelona since 14th century shows a strong impact of the urban and land uses changes. The Medieval walls protected the city from the flash floods of the water streams born in the near Collserola mountain until they were torn down in the middle of the 19th century (Barrera et al., 2006). Although Barcelona had a sewerage network since the time of Roman domination, the drainage network did not begin to be built until the end of 19th century (Martínez et al., 2014). This fact drove to a flood increase in the city. The biggest impulse in the drainage network came from the second decade of the 20th century and the definitive improvement was at the end of the 20th century with the construction of rainwater tanks (Martínez et al., 2014).

In this context, this contribution is devoted to the comparison between two events recorded previously and posteriorly to the main actions developed to cope with pluvial floods in the city. Pluvial flood events are a natural and recurring phenomenon at the end of the summer in Barcelona. They are due to short and very intense convective rain (Llasat et al., 2016b). The combination of these precipitation features and the geomorphologic features of the basins that cross Barcelona usually produce flash-floods. However, since all the streams that cross the city are covered and merged with the sewerage and drainage system (unitary water collection system), it is better to speak about "surface water floods" that always affect quotidian life in the city. It affects the transport and circulation in the city, produces power outages, floods in some streets and buildings, and sometimes human victims. Given the high population density and its economic and tourist activity as well as the relevant historic patrimony, among others, the impact is very high. This was what happened in the two episodes that are compared in this study. In both cases the oldest part of the city near the Montjuïc Mountain and the sea was the more affected, but traffic disruptions and local floods were produced in the entire city. In both cases the total accumulated rainfall was relatively low in comparison with this recorded on catastrophic flood events that have affected a wide region in Catalonia (near 400 mm in Barcelona Metropolitan Area in the October 1987 event), but rainfall intensity in 20-minutes overpassed the return period of 100 years.

In the 1995 event, the surface runoff of the streets caused a fatality in the Eixample quartier. A total of 2,500 calls were registered to the emergency services; 128,000 subscribers suffered cuts of light between 5 and 30 minutes; 2 blocks of houses were evacuated, and numerous low floors were flooded (La Vanguardia, 1995; CLABSA, 2015). There were numerous damages to street furniture and some cars were dragged. Damages in the gas network due to the inundation of control centres increased the pressure above the normal. As a result, there was a strong gas smell in certain parts of the city that caused an avalanche and the collapse of the Civil Protection telephone lines. 80 incidents were recorded in the sewerage/drainage network, such as floods produced by obstruction or in low points, etc. (CLABSA, 1995). The Romanesque monastery of Sant Pau del Camp was flooded. Floods also affected the surrounding region of Barcelona and one bridge collapsed. 33.6 Million $€_{2018}$ were paid by the national insurance company, CCS, to compensate insured losses in Barcelona.

In the 2018 event, 294 emergency phone calls were received from Barcelona, and the firefighters made 180 trips. Most of the calls were due to flooding of low plants and basements, water leaks or fallen trees. The consequences of rain on the city's infrastructure were 4 flooded metro stations, and two of them (Poble Sec and Paral·lel) were out of service 5 hours. The Filmoteca (film library and projection rooms) of Catalonia, the Monastery of Sant Pau del Camp and the Maritime Museum were flooded. There were also numerous lighting cuts that affected urban lines and owners. 3.5 Million $€_{2018}$ were paid by the CCS.

Descriptions of processes between events with a focus on risk management

Although the population increase in Barcelona between 1995 and 2018 was relatively low, the tourist activity was multiplied. Despite major changes in land uses were produced in the neighbor counties between 1995 and 2018 (Llasat et al., 2016a), where a great part of the agricultural soil were substituted by urban and industrial use and transport (roads, highways, airport), in the case of the Barcelona city, no major changes in land use have been produced after 2009. It is only observed an increase in asphalted streets and in recreative and green areas (that does not compensate the increasing of the runoff coefficient).

There are no significant changes in either the number of flood episodes or the maximum 1-day precipitation (RX1DAY) that have affected the Metropolitan Area of Barcelona (636 km^2 and a population of 3,239,337 inhabitants) between 1981 and 2015. However, there was a positive trend (but not statistically significant) in the number of flood events recorded in the 1981–1996 period, due to the increase in ordinary or minor floods. This increase could be mainly related to the urban development in this period (25.81% of new impervious surfaces). Conversely, for the 1996–2015 period, although there was an increase in impervious surfaces (around 20%), there was a decrease in the number of flooding episodes, thanks to the improvement of the sewerage system and the construction of water tanks in Barcelona after the 1995 event (Cortès et al., 2017). The 1995 episode marked a turning point in the development of the sewerage in the city. Although some major sewer works had already been carried out before the 1992 Olympics, it was thanks to this episode that there was a definitive boost from the City Hall to solve the flood problems of the city. In 1997 the Barcelona Special Sewerage Plan (PECLAB'97) was drafted and a diagnosis of drainage problems was carried out and a series of actions were proposed. High investments were made in structural protection for pluvial floods (Table 1). The regulation of flow rates in the Barcelona network was designed then through a series of underground retention deposits and slide gates. The result of the PECLAB'97, and its update with the Integrated Sewerage Plan of Barcelona (PICBA'06), has been the key element for the execution of up to 15 storm water retention tanks (13 underground tanks and 2 floodable areas), with a total capacity of 477,020 m^3. Nowadays the combined sewerage and drainage system of Barcelona is equipped with large unitary collectors that allow the evacuation of rainwater and residual waters, as well as rainwater retention tanks that allow regulating the flow rates and volumes of rainwater circulating for the network. The runoff produced by the local storms is conducted through the inlets located on the street to the sewer system that also acts as a drainage network.

Table 1 Investments in infrastructure for pluvial flood risk management

Period	Investments (as at implementation)	Costs of investment as at 2018
2000-2004	51.25 million € (font http://hdl.handle.net/11703/89578)	65.04 million €
2006	5.1 million € (font http://hdl.handle.net/11703/89580)	6.08 million €
2009-2010	26 million € (font http://hdl.handle.net/11703/87899)	28.24 million €
2011	35 million € (font http://hdl.handle.net/11703/87905)	37.13 million €
2000-2011	total investments in water tanks and rainwater collectors: 117 million €	136.49 million €

The design and development of these large underground infrastructures has enabled storage of the peak of rain and management of the flood. In addition to improving the impact on the receiving environment since the regulation allows to reduce the CSO discharges in the environment. The plans have also promoted the change in the type of inlets to favor the maximum catchment of water in surface as well as increasing the density of the inlets and grates of water capture in most streets, to reduce the clogging phenomena produced by leaves or plastics. Some experimental studies have showed that the clogging phenomena reduce considerably the capacity of inlets to connect the surface rainwater to the sewer (Valentin et al., 2018).

Event comparison in respect to pluvial flood hazard

21 September 1995. Three days before the episode, 15.3 mm of rain were collected in average in the city. Subsequently there was no rainfall until September 21. The storm started in the North of the city, over the catchment of the Besós River, and moved towards the city of Barcelona achieving its maximum activity on the city centre. No lightning data were available on this year, but the high number of electricity cuts points to a great electric activity in the atmosphere. The images of the meteorological radar that the INM (National Meteorological Institute) had just installed near Barcelona show that it was a multicellular system, stationary over the city for about two hours, which gave place to a very convective episode (Llasat et al, 2016b). The weather type was characterized by a NE advective type (Gilabert and Llasat, 2017).

The rainfall event over the city lasted near 4h, from 21:40 h (official time) of 21 September 1995 until 01:30 h of 22 September, being the period of maxima intensity near 22:50 h. The maximum 5-min rainfall intensity was of 235 mm/h, with an average 20-min rainfall intensity of 155 mm/h. These quantities correspond to a return period above 100 years, when the sewage system is projected for a return period of 10 years (CLABSA, 1995). Despite these intensities, the maximum precipitation cumulated in Barcelona in the entire event was of 91.9 mm, and the average precipitation recorded in the city was of 38 mm in less than 4 hours. It was a very convective event (more than 80% of the precipitation was convective, with a 5-min intensity above 35 mm/h) (Llasat et al, 2016b).

6 September 2018. The last previous precipitation in Barcelona was recorded between 31 August and 1 September (5 days before the event) with a total amount of 27.5 mm. The storm system arrived at the city of Barcelona from the south near 02:30 h (official time) of 6 September 2018 (BCASA, 2018). Although it was in its ending phase, when it arrived to the south of the city (Hospitalet de Llobregat) it reactivated and remained stationary over the center of the city, near the sea. Probably, the Montjuïc mountain, that is near the sea, developed a relevant role both in the reactivation of the precipitation system and the stationarity of the process. The weather type was characterized by a NE advective type (Gilabert and Llasat, 2017).

The rainfall over the city lasted until 23:50 h that means a total time of 21:20h and affected all the city. Maximum intensity was produced at 03:25 h, with a maximum 20-min intensity of 169,8 mm/h, that is the maximum recorded in the city since data are available (1995), with a 5-min peak of 211 mm/h. The 20-min intensities overpassed the return period of 10 years in 42% of the stations that composed the rainfall network managed by BCASA (21 in that year). The average precipitation estimated in the city was of 45 mm in 21h and a punctual maximum of 83,8 mm for the same period in the Olympic Village (BCASA raingauges network). The images of the meteorological radar network of METEOCAT (Catalan Meteorological Service) confirms that it was a mesoscale convective system that was generated over the sea, with a remarkable convective activity (Figure 1, yellow, orange and red areas). This strong convective activity was corroborated by the 194 lightning recorded over the city of Barcelona, plus hundreds of lightnings recorded over the sea.

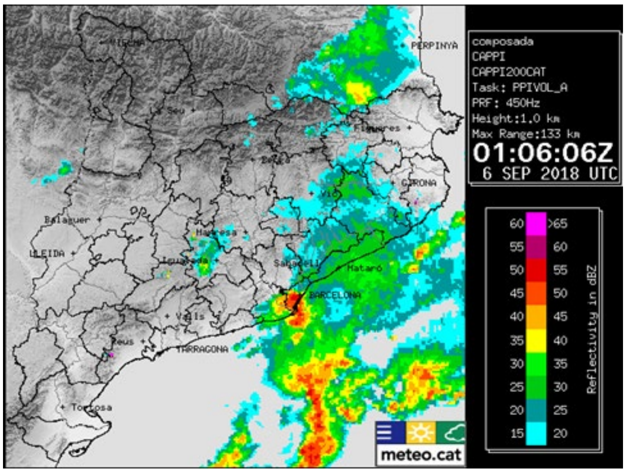

Figure 1. Radar imagery corresponding to an altitude of 1000m at 01:06:06 UTC, 6 September 2018. Red colours show maximum rainfall intensities. Source: METEOCAT

Event comparison in respect to exposure

Figure 2 shows the map of Barcelona. It is possible to identify the oldest part of the city (red area) that has a great exposure to pluvial floods due to the old buildings and cultural heritage (medieval and roman) that in some cases difficult developing souterrain works as to build rainwater tanks, the low economic level of a great part of people living in it (mainly immigrants) and the frenetic touristic activity. The old village of Gracia that is nowadays into the Barcelona city is also in red due to the high concentration of inhabitants and tourism and the old buildings, with a great activity in the streets. In the case of l’Eixample (black area) and Ciutat Vella (red area) exposure hostpots are mainly related with cultural heritage (modernism), touristic and economic activities, and high population density. This exposure has increased from 1995 to 2018, due to the increase in tourist pressure, as well as the commitment of the council to give impetus to a marginal area like Ciutat Vella locating new cultural infrastructures, such as the Catalunya film library.

The 1995 event mainly affected Ciutat Vella and Gràcia (red area in the map), l’Eixample (black area in the map), Gràcia, les Corts and Sarrià (yellow area in the map). This event was produced during the Merce holydays that is the major feast in Barcelona. Consequently, a great part of the non-permanent structures created for this event were destroyed. The 2018 event mainly affected Montjuïc and Ciutat Vella (red area near the sea), l’Eixample and Sant Martí (black area). Although the event started on the night it last until the next morning, when people come back to its regular activity. Because of it, the number of calls to the emergencies system increased on the morning.

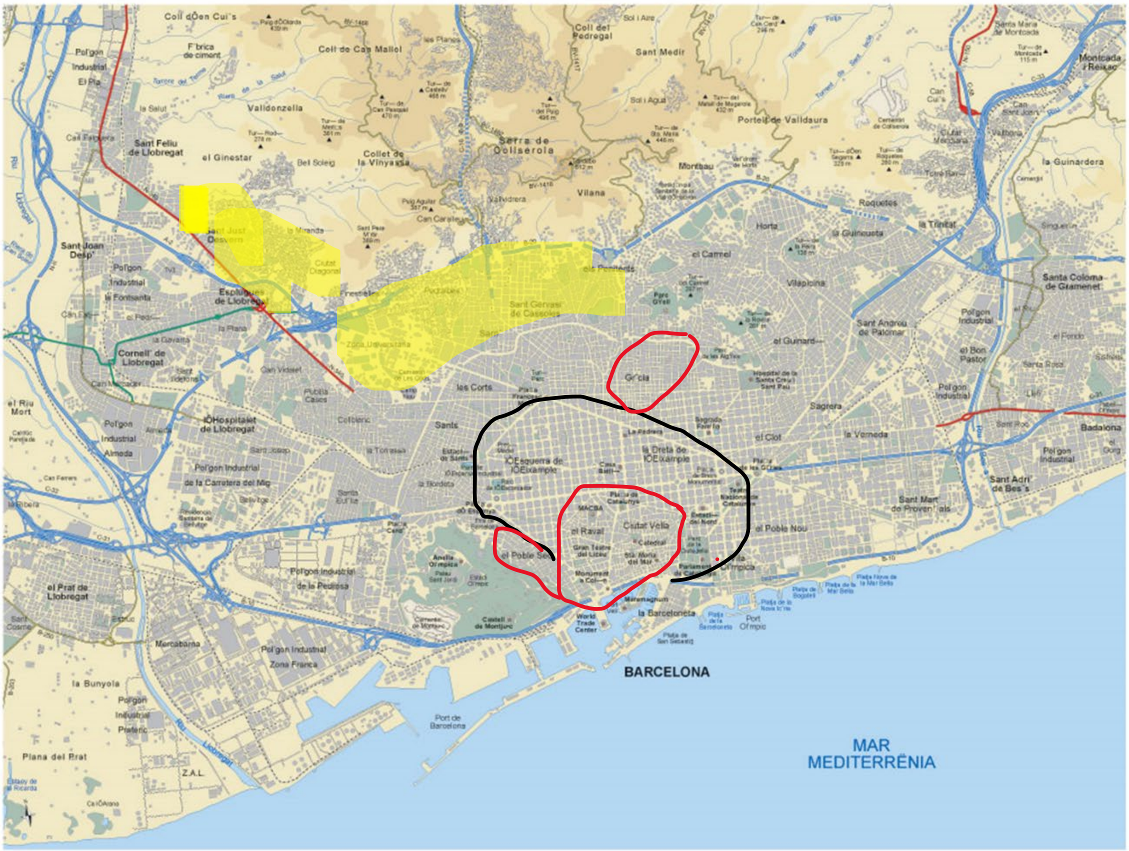

Figure 2. Map of Barcelona city. Red line shows the oldest part of the city, and the old village of Gracia; black line surrounds the "Eixample" and yellow area shows the part of the city with the highest standards of life. The major green area near the sea is the Montjuïc Mountain

Event comparison in respect to vulnerability

In 1995 the only meteorological service that provide operative warnings in Spain was the Instituto Nacional de Meteorologia (INM, nowadays AEMET, Agencia Estatal de Meteorología). The surveillance was made following the Meteosat imagery and the available meteorological synoptic models at that time. However, on the afternoon of 21 September, the precipitation system over the city was developed suddenly and was not detected by the people responsible of monitoring and forecasting. The civil protection services were not alerted by INM about the rain that was being registered. When at 21:30 h INM tried to contact Civil Protection, the phone lines collapsed and the fax for the official communication INM-Civil Protection was not sent correctly. At 22:30 h Civil Protection started its emergency actions without any existing weather forecast. The warning of the INM arrives finally by telephone at 23 h. Although the company responsible of the sewer system managing (CLABSA in that time, BCASA nowadays) didn't received any warning, they triggered their warning system. In this case the employees of the sewer management company had the obligation to move to the CLABSA headquarter and manage the episode, but the state of the streets did not allow them to arrive at the center of control.

In 2018 meteorological early warnings were provided by the Meteorological Service of Catalonia (SMC) and AEMET. The forecast made by AEMET at 12:00 UTC of 6 September gave a probability of 60% of "moderate/heavy storm" during the night. SMC forecast of 5 September showed a low probability of overpassed the rainfall intensity of 20 mm in 30 minutes along 6 September. During the event the SMC reported that a Rainfall Intensity Observation Warning (more than 40 mm in 30 min) was issued at 02:30 UTC. Both meteorological services have networks constituted by automatic raingauges, meteorological radars and lightning detectors. Both of them run mesoscale operative models each 6 hours and satellite information provided by MSG (Meteosat Second Generation) that helps to monitoring. The research developed in last decades has improved the precipitation estimation from radar and the storm tracking and nowcasting. Both meteorological services has a specific warning protocol that follows the standard proposed by the WMO (World Meteorological Organization), although they do not have the same warning thresholds. BCASA has also a control center that receives all this information.

In 1995 the data of rain gauge and sewer sensors had a reception technological system non-robust. The fatality occurred forced the City Council to make the investment necessary to develop a centralized operation room for the sewer network with a confinable SCADA (Supervisory Control And Data Acquisition) and communication system. At the same time the alert protocols in case of rain were developed. Since 1997 the SCADA system receives in real time the information from this network and it is applied the early warning system in coordination with Civil Protection depending on the rain intensity. The SCADA system and the centralized operation control centre allow to do, jointly with the storm water retention tanks construction, the real-time management of network devices. That means the underground tanks are managed automatically depending on the water levels in the pluvial network near each them. For each storm water tank several PLC's (Programmable Logic Controller) are programmed to receive all tank data and other close sewer network data. Pre-defined conditions to manage the flows inside the storm water tank have been programmed in the PLC's. All these data are sent automatically to the control centre, and from this the operators can decide to modify the set points or operate manually a device.

Summary

From a pluviometric point of view the 2018 event had a major hazard component due to the major extension and duration of heavy rainfalls that affected the greatest part of the city, giving place to an average precipitation of 45 mm in comparison with the 38 mm recorded in the 1995 event. Antecedent conditions were similar in both events. The maintenance service improved from the first event to the second (nowadays it is automatized and includes tasks made by robots in sewers with difficult accessibility), and in spite some inlets were clogged by leaves, the relative number was inferior in the 2018 event. Although exposure has increased between both events, mainly as a consequence of the great increase of touristic activity and assets value, flood damages on the second event were considerably less than in 1995. From 1995 to 2018 the early warning system was improved considerably and the communications have been developed and made accessible enormously comparing both years. The 1995 episode marked a turning point in the development of the sewerage in the city. Although some major sewer works had already been carried out before the 1992 Olympics, it was thanks to this episode that there was a definitive boost from the City Hall to solve the flood problems that the city suffers recurring. On the contrary, no change in awareness and precaution of the population in face to these events has been produced.

In conclusion, main changes between both events have been:

Management aspects: a) drainage system: great improvement; b) Pluvial flood risk management aspects: great improvement;

Hazard: a) antecedent conditions: similar; b) precipitation/weather typology: similar; c) severity: major in the second event

Exposure: a) number of people exposed: the number of residents exposed has slightly decreased but the number of tourists has enormously increased; b) Number of buildings exposed, settlement area exposed and amount of *assets exposed*: although the number of buildings has decreased the value of the assets exposed has increased; c) Exposure hotspots: slightly increase due to the strong commercial and touristic activity in the areas that are usually affected by pluvial floods and the construction of new hotspots in flood prone areas.

Vulnerability: a) Awareness and precaution: not change; b) Preparedness: improvement in the official institutions but not between population; c) Organisational emergency management: great improvement; d) Coping capacity: improvement

Impacts: a) Number of fatalities: decrease (from 1 to 0); b) Number of affected people: decrease in the number of houses flooded, but increase in the people affected in their regular life; c) Number of destroyed houses: none in both events, but in the first event temporal structures prepared for the City celebrations were completely destroyed; d) Direct economic impacts: major in the first event in spite the increase of insured dwellings.

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ID 13

Paired flood events: 1998 and 2017 floods in the Piura region, northern Peru

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Short description of both events with a focus on impacts

This case study investigates the characteristics and impacts of subsequent El Niño related flooding in the Piura region of north Peru (Fig 1). Strong El Niño episodes cause extreme precipitation in what is otherwise an arid region, resulting in a combination of pluvial and fluvial flooding combined with secondary hazards such as landslides. At the national scale, the 1997-98 event caused around USD 3.5 billion of damage, with 366 deaths and 0.53 million people affected (Venkateswaran et al., 2017), while the 2017 event caused USD 3 – 9 billion in damage, with 159 deaths and 1.4 million people affected (Venkateswaran et al, 2017; INDECI, 2017).

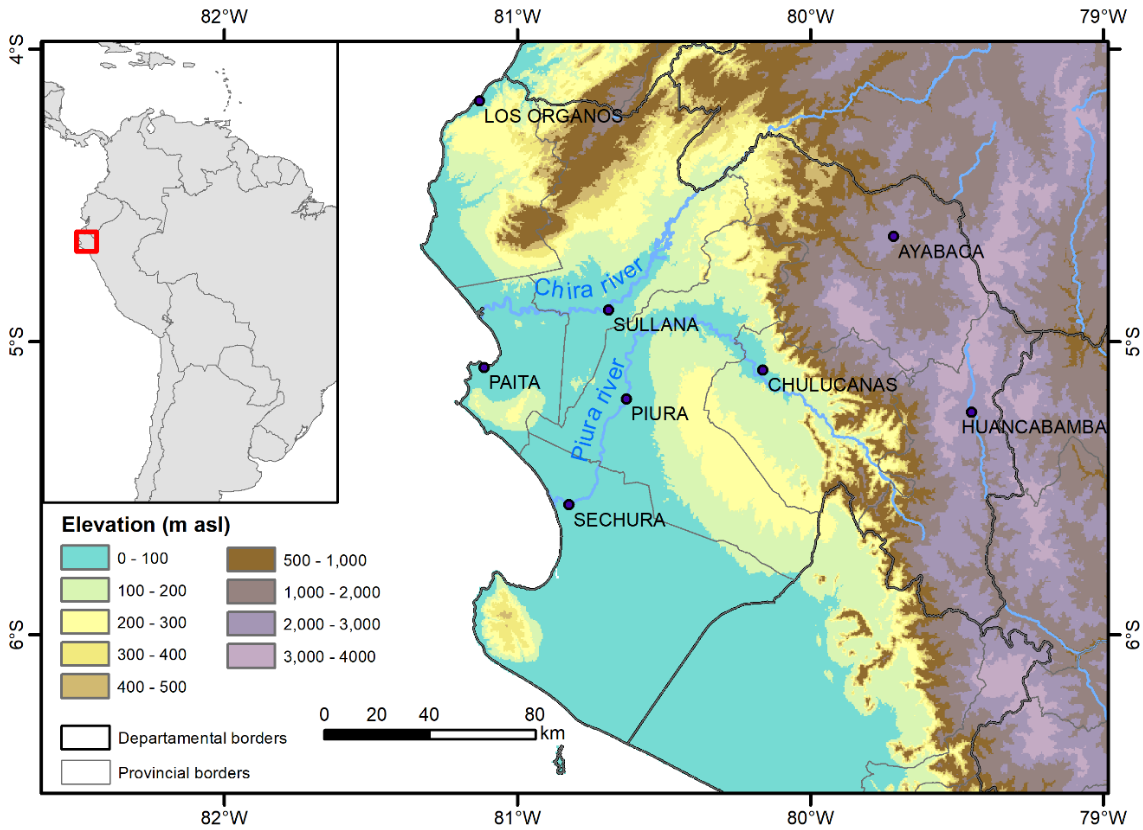

Fig. 1: Main geographical features of the study region (Piura region, northern Peru).

For the Piura region specifically, the 1998 event affected 720,000 people and caused 42 deaths. It destroyed 13,600 houses and damaged another 24,000. Around 6,800 ha of agricultural crops were destroyed, with another 4200 ha of crops affected, while 142 km of roads were destroyed.

The 2017 event affected 336,000 people and caused 18 deaths. Around 329 km of roads were destroyed, and a further 29,000 km affected. Agricultural damage amounted to 14,700 ha of crops, of which 8,500 were destroyed. 6400 houses collapsed, 7900 were rendered uninhabitable, and another 76000 were affected. 434 schools and 212 health posts were damaged (INDECI, 1998; CAF, 2000; Venkateswaran et al., 2017; INDECI, 2017).

Descriptions of processes between events with a focus on risk management

Peru is a country with a high economic growth rate (an average per year of 7% between 2005 and 2011) and therefore the socio-economic context has changed considerably between the 1998 and 2017 events. This has led to positive and negative evolutions. On the one hand, interventions and actions of both governmental and non-governmental organizations have increased resilience and preparedness. For example, the national hydrometeorological service SENAMHI issued both medium-range weather forecasting for the 2017 event (which allowed building preparedness in the months and weeks before the episode) as well as short-range river flow forecasts, which allowed for specific warnings in and around affected rivers (SENAMHI, 2020).

The operational practice of the national hydrometeorological office SENAMHI consists of daily river flow forecasts and associated warnings at a national level. Additionally, they provide medium-range weather forecasts with a lead time of up to 3 months (SENAMHI, 2020). Early warnings of an “extraordinary” el Niño episode were issued as early by the specialised government body ENFEN in 2015, which were updated and refined in the months before the event based on observations and forecasts of sea surface temperature. The SENAMHI river flow forecasts and flood alerts did not yet exist for the 1998 events. Although weather forecasts existed, it can be assumed that these were much less precise than for the 2017 event.

In addition, the institutional framework for disaster prevention and mitigation has improved significantly between the two events (e.g., Organización Panamericana de la Salud; 2018). The governmental institutes in charge of the national disaster risk prevention system are the National Institute of Civil Defence (INDECI), and the national Centre for the Estimation, Prevention, and Reduction of Disaster Risk (CENEPRED), both of which were founded in 2011. Both have extensive information dissemination capacity, including web portals, including a database of past extreme events, vulnerability maps, and manuals for local governments, institutes, and NGOs.

Meanwhile, NGOs such as Practical Action (locally known as *Soluciones Practicas*) have implemented disaster risk reduction activities, including evacuation exercises and awareness campaigns (French and Mechler; 2017).

However, various socio-economic trends have also led to an increased exposure to floods. The most important driver is population growth and urbanization, which in turn has led to an encroachment of the riverbed and floodplain areas (INDECI, 2017). Many of these consist of informal settlements and dwellings inhabited by the poorest segment of society.

Lastly, new urban planning rules and disaster mitigation strategies have been introduced between the two events. The most significant of those is the law for the creation of a national system for disaster risk management (SINAGERD) in 2011, implemented through a dedicated governmental institute (CENEPRED). However, the poor enforcement of existing laws and regulations, for instance regarding the prevention of encroachment of flood plans, is a major bottleneck (Venkateswaran et al., 2017).

Event comparison in respect to flood hazard

The coastal area of northern Peru is characterised by an arid climate with typical annual precipitation amounts ranging between 20 and 100 mm/year resulting from low sea surface temperatures along the Peruvian coast.

However, el Niño episodes are associated with the warm phase of the ENSO oscillation in the Pacific Ocean, which causes an anomalous increase of the sea surface temperature off the coast of northern south America. This causes severe precipitation events over a period of 3 – 4 months (January – April) and associated, a combination of pluvial and fluvial flooding over the entire northern coastal area of Peru, but with its epicentre in the region of Piura.

The 2017 event was an unusual El Niño episode, and referred to as a "coastal El Niño". Compared to typical El Niño events, the pattern of sea surface warming of a coastal El Niño is more concentrated along the coast of northern and central Peru (Takahashi and Martinez, 2017). This led to less intense rainfall over the Piura region in the 2017 event compared to the 1998 event.

During the 1998 event the yearly precipitation[1] in the Piura was 2181 mm, of which virtually all fell during the wet season according to the PISCO precipitation product of SENAMHI, Peru (SENAMHI, 2020). The temporal distribution consists typically of a discontinuous series of high intensity rain storms. The El Niño episode of 2017 was less intensive (Takahashi and Martínez, 2017). An annual total of 1483 mm was recorded; however daily extremes were as high as 258.5 mm in 24 hours (Partidor gauging station, Tambo Piura).

This pattern also reflected in the extreme river flows. The Piura river, which is the largest river in the Piura region, recorded a maximum flow of 3367 $m^3 s^{-1}$ during the 1998 event, and 2754.5 $m^3 s^{-1}$ in 2017 (ENFEN, 2017).

Event comparison in respect to exposure

According to national census data of 1993 and 2017 (INEI, 2020), the population of the region of Piura increased from 1.39 million inhabitants in 1993 to 1.86 million in 2017, while the number of settlements increased from 291,748 to 372,187. This is accompanied by an increase in urbanization, with the share of settlements in urban areas increasing from 70.5% to 74.1%. Peru has a high number of informal settlements, which are often located in areas prone to natural hazards such as landslides and flooding (French and Mechler, 2017). Most of these informal settlements are in urban areas where pressure on available land is highest. Although no direct data are available, the share of urban settlements is therefore a useful proxy for the share of informal settlements and suggests an increase in population density in floodplains.

In terms of geographical area, according to INEI (2017) the 2017 event affected the entire region of Piura (35,892 km^2), while the 1998 event affected the whole region except for the province of Sechura (Fig. 1), which amounts to an affected area of 28,522 km^2. But despite its size, the Sechura province has a low population number (79,117 in 2017) and therefore has only a minor impact on the number of people affected.

In addition to population growth, the density of infrastructure has increased markedly between the two events, thus increasing the exposure. Although very few quantitative data are available,

[1] September 1997 – August 1998

a useful proxy is the length of the road network, which has increased from 78 216 km in 2000 to 156 792 km in 2013 for the entire country (INEI, 2014).

Event comparison in respect to vulnerability

The presented data show a marked shift in the nature of the damage. Prevention and awareness campaigns, improved weather and river flow forecasting, better crisis management, and better response logistics (e.g., transport, mobile communication) are most likely responsible for the lower number of deaths and people affected in 2017 compared to 1998 (Venkateswaran et al., 2017). These activities are institutionalized since 2011 by the establishment of INDECI and CENEPRED.

In contrast, material damages are at least as high and most likely higher than in 1998, despite evidence that the magnitude of the hazard was lower. We attribute this to the strong increase in urbanization, both formal and informal, and increase in agriculture. Although the share of agriculture in the GDP has remained almost constant, its total value has increased from US$4.44 billion in 1998 to US$ 14.35 billion in 2017. This can be attributed mostly to an increase in large-scale industrial agriculture in the coastal area, which is particularly vulnerable to ENSO events. Additionally, the destruction of bridges caused problems in the agricultural supply chain, in which products could not be transported from the farms to the major cities for selling or overseas transport (Venkateswaran et al., 2017; French and Mechler, 2017; INDECI, 2017).

Summary

Notwithstanding the slightly different nature of the hazard, the marked socio-economic development in the affected region has resulted in a clear shift in the type of risk and damage associated to El Niño related flooding. Improved disaster risk reduction and preparedness is likely to reduce the direct human toll of the flooding. At the same time, the combined trends of population growth, infrastructure building, informal settlement expansion, and economic activity have increased the exposure and vulnerability of infrastructure and with it the economic damage. This is further exacerbated by the infrequent nature of the events and their extreme nature (e.g., people building houses in riverbeds that are only active during an El Niño event).

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ID 14

Paired riverine flood events: 2000 and 2011 riverine floods in Cambodia

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Short description of both events with a focus on impacts

The 2000-2001 and 2011 historical floods which affected the Tonle Sap Lake Basin were caused by two factors:

i) meteorological conditions characterized by important rainfall excesses in Cambodia and the whole Mekong Basin (MRC, 2015) induced by the combined impact of negative extreme El Niño Southern Oscillations (ENSO) and Pacific Decadal Oscillations (PDO) indexes values (Delgado et al., 2012; Frappart et al., 2018; Räsänen and Kummu, 2013). Figure 1 presents the monthly rainfall from the Global Precipitation Climatology Centre (GPCC, Becker et al., 2013) and Climate Research Unit (CRU TS v.4.03, Harris et al., 2014) datasets averaged over Cambodia of the 1980-2015 (grey), 2000 (blue), 2011 (orange). In 2000, above average rainfall were observed from April to August, whereas in 2011, excess in rainfall were mostly recorded in September.

ii) hydrological floods due to critically high water levels in the Mekong mainstream (MRC, 2015) causing Mekong flood pulses, which are the major water supply to the lake, of large amplitude (Delgado et al., 2012; Frappart et al., 2018; Räsänen and Kummu, 2013).

Their combined effects were responsible for large positive anomalies in river levels (MRC, 2015) and in the lake level and surface water storage in the Tonle Sap Lake Basin (Frappart et al., 2018). Figure 2 presents the monthly lake levels averaged between 1993 and 2018 with associated standard deviation (std, black), for 2000 (blue) and 2011 (orange) based on radar altimetry data. In 2000, the lake level was above normal (mean + 1 std) during the whole year whereas above average values were observed from July to December in 2011. If the peak flood duration was longer in 2000 than in 2011, a slightly higher value was recorded in 2011 than in 2000; keeping in mind that the monthly lake value is obtained using 3 altimetry-based water levels in 2000 and 4 in 2011.

These two extreme events caused a huge number of casualties (347 in 2000 and 250 in 2011) and affected 387,000 people in 2000 and 145,000 in 2011 in Cambodia (MRC, 2015). Their direct economic impacts were estimated ranging from 151 to 160 million US $ for the 2000 flood and ranging from 100 to 160 million US $ for the 2011 flood (MRC, 2015). Increase in water-borne diseases (e.g., cholera and acute diarrhoea) was observed for both events (Davies et al., 2015; Saulnier et al., 2018). In 2011, Angkor World Heritage Site experienced its worst flood in 50 years (Liu et al., 2019)

Descriptions of processes between events with a focus on risk management

The National Committee for Disaster Management (NCDM) was established in 1995. It is composed of members from different Ministries, Cambodian Armed Forces, Civil Aviation Authority and Cambodian Red Cross. Its objective is to coordinate the management of natural disasters (Oudry et al., 2016). After the major flood of 2000, improvements in risk management were undertaken at local, national and basin levels. Provincial Flood Preparedness Plan (FPP) and district FPP were updated and published (Chea and Sharp, 2015), NCDM organized annual seminars to prepare the provincial preparedness plan before each flood season under the Flood Management and Mitigation Programme 2004-2010 Component 4 “Flood Preparedness Management Strengthening” the provincial and district Committees for Disaster Management of each province along the Mekong including strategies for flood prevention, teaching safety measures, providing flood early warnings, … (National Committee for Disaster Management and Ministry of Planning, 2008). The Mekong River Commission (MRC) plays a basin-wide role in flood management in the framework its Flood Mitigation and Management Programme (FMMP 2004-2011) but with no mandate to physically manage flood risk (MRC, 2011), leading to the establishment of a Regional Flood Management and Mitigation Centre in Phnom Penh (Cambodia), which provides technical and coordination services to the four countries (Laos, Thailand, Cambodia and Vietnam) in the Lower Mekong Basin and the development of a flood forecasting system.

These two major flood events were driven by the La Niña phase of ENSO events, enhanced by the PDO, which caused the positive anomalies of rainfall (Delgado et al., 2012; Frappart et al., 2018; Räsänen and Kummu, 2013). Changes in land use/cover show important deforestation and growth in agricultural areas since 1990 causing an increase of erosion in the upper watershed and floods downstream (Senevirathene et al., 2011).

Event comparison in respect to riverine flood hazard

The floods of 2000 and 2011 were ranked 1st and 7th largest floods since 1966 (Cosslett and Cosslett, 2018). The 2000 flood was considered to be the worst which occurred in Cambodia during the last 70 years according to the Cambodian government. The following hydrological parameters were considered: the monthly rainfall in Cambodia in 2000, 2011 and the 1980-2015 monthly rainfall climatology, the standardized anomaly index of rainfall in the whole Mekong Basin which is related to regional climatic conditions and the surface water level, storage and extent of the Tonle Sap, the largest lake of the Mekong Basin, located in Cambodia. The standardized anomaly index (SAI) defined by (Kraus, 1977) to study long-term rainfall variations as:

$$SAI(k) = \frac{1}{n}\sum_{i=1}^{n}\frac{R(i,k) - \mu(i)}{\sigma(i)}$$

where R(i,k) is the annual rainfall at station i for year k, μ(i) and σ(i) are the annual average and standard deviation over the reference period for station i, respectively, and n is the total number of grid points in the Mekong Basin from the TRMM 3B43 rainfall product.

SAI values between 0 and 1 (-1 and 0) correspond to mild wet (dry) conditions, between 1 and 1.5 (-1.5 and -1) to moderately wet (dry) conditions, between 1.5 and 2 (-2 and -1.5) to severely wet (dry) conditions and above 2 (below -2) to extremely wet (dry conditions). SAI was above 2 in 2000 and above 1 in the whole Mekong Basin (Frappart et al., 2018). Water levels measured in different locations of the Mekong River and its tributaries in Cambodia were above the 1960-2010 long term daily average during the whole rainy season (see Table 1). Very similar annual maximum of water levels and inundation extent were recorded in Cambodia (MRC, 2015). In the Tonle Sap Lake drainage area, which is the largest lake and wetland ecosystem in the Mekong Basin (MRC, 2005), flood extent above 14,000 km^2 and water levels above 12 m with reference to WGS84 datum were observed for both events (Fig. 2), leading to surface water storage inter-annual anomalies above 30 km^3 for the 1993-2016 time-period (Frappart et al., 2018)

Event comparison in respect to exposure

They affected a large part of Cambodian territory (21 and 18 out of 24 provinces in 2000 and 2011 respectively) , exposing 3.5 and 1.77 millions of people in 2000 and 2011 respectively (Sok Bun Heng, 2011; MRC, 2015). In these provinces, 318,000/268,000 houses, 988/1360 schools, 158/115 health centers and hospitals were damaged in 2000 and 2011 respectively. 374,100/267,00 ha of rice crops and 47,460/17,300 ha of other crops were destroyed or damaged in 2000 and 2011 respectively (MRC, 2015). Moreover, 2,621/925 km of national and provincial roads, 1,500/4,470 km of secondary roads and 115/177 bridges and culverts were affected in 2000 and 2011 respectively (IFRCRCS, 2002; ADB, 2012; NCDM and UNDP, 2014).

Event comparison in respect to vulnerability

After the flood of 2000, the focus in regional flood emergency planning activities was changed from response and relief activities to supporting community-based activities aimed at flood preparedness and vulnerability reduction (MRC, 2015). The NCDM was in charge of the awareness, precaution and preparedness in the framework of the Flood Management and Mitigation Programme 2004-2010. Its task was mostly on prevention, formation and early warnings. The Cambodian government mostly relies on the Cambodian Red Cross to assist them in emergency response based on local (July) and international (September) appeals (IFRRCS, 2002). Organizational emergency management and coping capacity, developed as a consequence of the floods of 2000 and 2002 are summarized in (Chea and Sharp, 2015) for the flood of 2011. They consist in reporting the flood situation and assessing damages, monitoring and evaluating the relief activities, transferring and providing health care to victims. The coping capacities mostly concerned rehabilitation and reconstruction of damaged infrastructures with 55 million US $ transferred to restore key infrastructures in the worst-hit provinces, water and sanitation activities. Economic activities were also supported through macroeconomic stabilization budget (e.g., USAID/OFDA) and revitalization of affected sectors (agriculture, natural resources, public transportation) with 3 million US $ of support by ADB (Chea and Sharp, 2015) after the flood of 2011 as a consequence of this event.

Summary

The floods of 2000 and 2011 in Cambodia were ranked 1^{st} and 7^{th} largest floods since 1966 (Cosslett and Cosslett, 2018). The main drivers of these two flood events are the La Niña phase of ENSO events, enhanced by the PDO, which caused the positive anomalies of rainfall (Delgado et al., 2012; Frappart et al., 2018; Räsänen and Kummu, 2013). The intensity of the ENSO event was higher in 2000 than in 2011, but the peak of the rainy season occurred earlier (July) in 2000 than in 2011 (September) in Cambodia (Fig. 1). The flood of 2000 in Cambodia was mostly due to regional climatic factor causing a large flood of the Mekong River whereas the flood of 2011 in Cambodia was caused by the concomitancy of both the peak flood of the Mekong River and higher than usual rainfall during the rainy season. Changes in land (important deforestation and growth in agricultural areas) aggravated the flooding in downstream areas (Senevirathene et al., 2011). 21 and 18 out of 24 Cambodian provinces were affected in 2000 and 2011 respectively, exposing 3.5 and 1.77 millions of people and damaging 374,100/267,00 ha of rice crops and 47,460/17,300 ha of other crops in 2000 and 2011 respectively (Sok Bun Heng, 2011; MRC, 2015). The floods were responsible for an increase in water-borne diseases (e.g., cholera and acute diarrhoea) (Davies et al., 2015; Saulnier et al., 2018). In 2011, Angkor World Heritage Site experienced its worst flood in 50 years (Liu et al., 2019). Their direct economic impacts were estimated to reach up to 160 million US $ for both flood events (MRC, 2015). After the major flood of 2000, improvements in risk management were undertaken at local, national and basin levels to improve preparedness of the population, early warnings and crisis management (MRC, 2011; Shea and Sharp, 2015). The number of casualties, of building and crops damaged due to the flood was lower in 2011 than in 2000. Nevertheless, preparedness system needs to be improved: more funds are necessary to support material and formation of specialists. Emergency response is still mostly under Red Cross responsibility. Rehabilitation and recovery are still at early stage of development (Chea and Sharp, 2015).

Figures

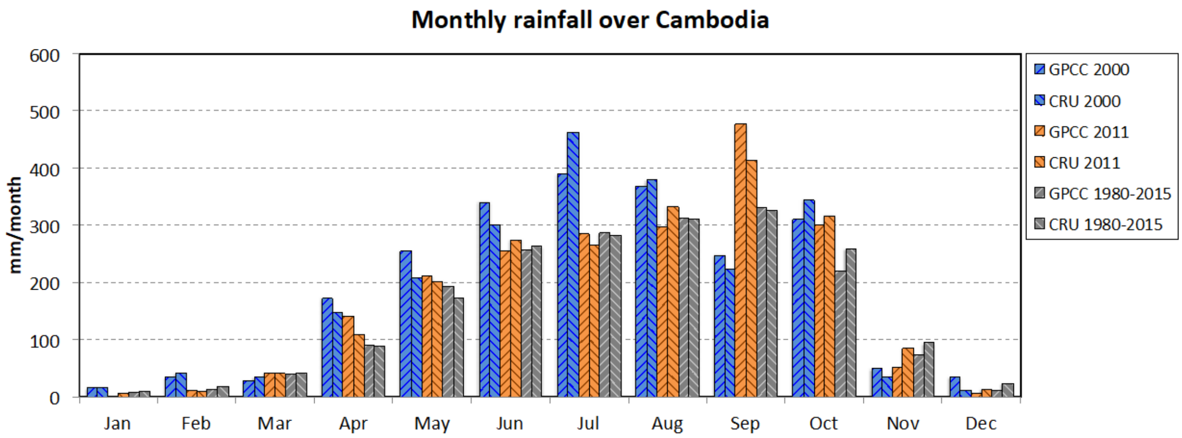

Figure 1 : Monthly rainfall over Cambodia from CRU and GPCC averaged between 1980 and 2015 (grey), for 2000 (blue) and 2011 (orange).

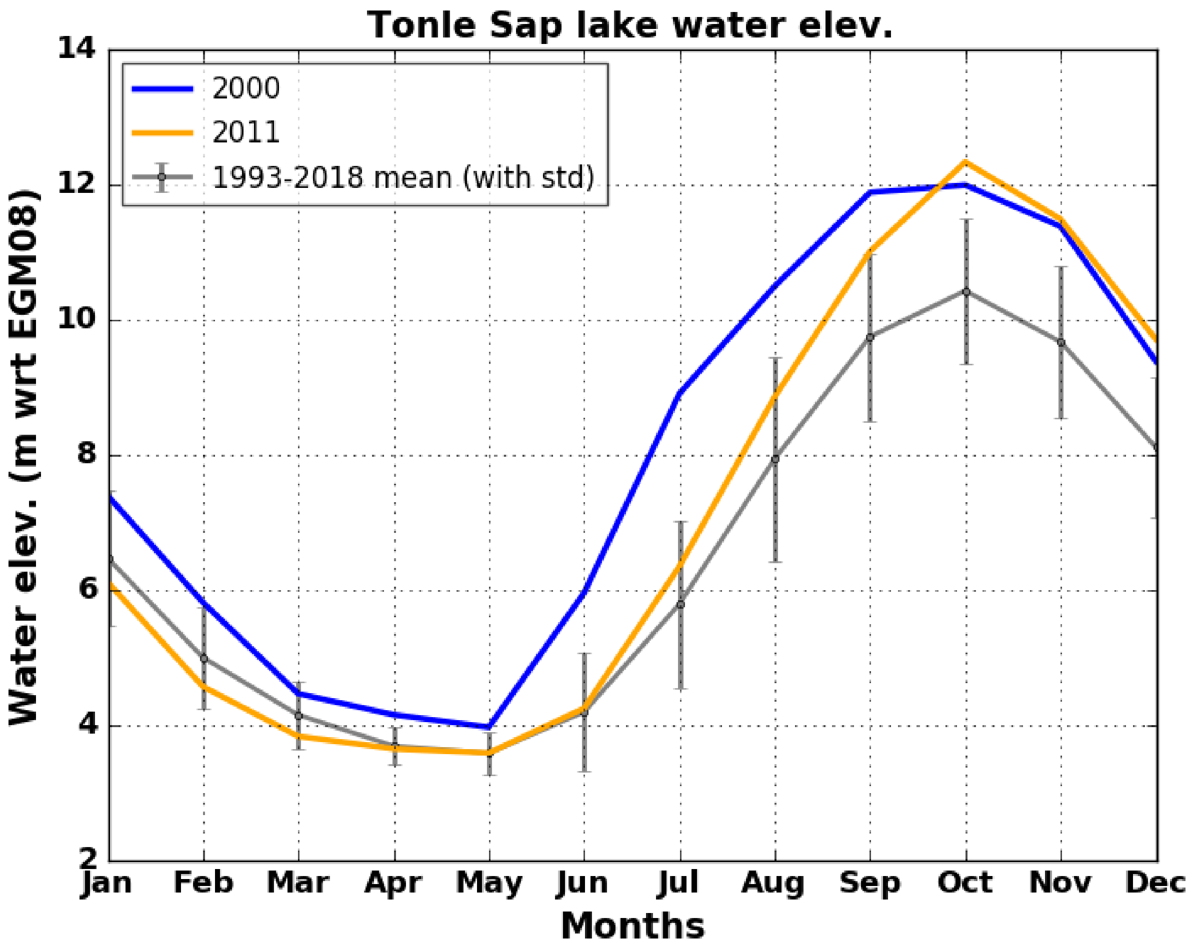

Figure 2: Monthly lake levels averaged between 1993 and 2018 with associated standard deviation (black), for 2000 (blue) and 2011 (orange) based on radar altimetry data.

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ID 15

Paired riverine flood events: Comparison of 2013, 2002 riverine floods in the Upper Danube catchment in Germany and Austria

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Short description of both events with a focus on impacts

The Upper Danube basin was affected by two major riverine floods in 2013 (May 29th-June 4th) and 2002 (August 7th – 12th) (Blöschl et al., 2013). Both summer floods occurred as a consequence of atmospheric blocking situations leading to the Atlantic moisture transport to the European Alps with additional moisture collected from the Mediterranean region transported by the so-called "Vb" cyclon tracks northwards (Ulbrich et al., 2003, Blöschl et al., 2013). Whereas the precipitation during the 2013 event was centered on the northern rims of the eastern Alps, the 2002 event affected the Upper Danube basin and Bavarian Forest more strongly. Dyke failures during 2013 caused extensive inundation near Deggendorf along the Bavarian Danube and the Isar tributary. For the 2013 flood, 5 victims are reported in Austria (ICPDR, 2014), whereas 9 people lost their lives in the 2002 flood (EM-DAT, 2019). The total damage to private and state property including the infrastructure facilities amounted to approximately 1.45 billion € in Germany and 0.87 billion € in Austria (ICPDR, 2014). The estimated total direct losses in Austria for the 2002 flood amounted 3.2 billion € (ICPDR, 2014) and ~0.2 billion € in Germany (i.e. a total of about 4 billion € as at 2013) (Kron, 2015, DKKV, 2015). More than 10% of losses in Austria during the 2013 flood were encountered in the transport and critical infrastructure sector (ICPDR, 2014).

Descriptions of processes between events with a focus on risk management

The 2013 flood was hydrologically more severe in the Upper Danube basin than the 2002 flood. The flood losses in the German part of the basin were indeed higher for 2013 than in 2002 (DKKV, 2015). However, in Austria the flood losses were significantly reduced. Austria invested 2 billion € into the reinforcement of flood protection since the previous flood, and an additional 1.6 billion € were spent in Bavaria from 2001 till 2014 (ICPDR, 2014). Since 2004 restoration measures on the lowland tributaries were undertaken. This led to the effective reduction of water levels during the 2013 flood (ICPDR, 2014). For example, at Salzach near Niedernsill in Austria, retention capacity was increased by 70,000 m^3 from 2004 till 2007 (BLFUW, 2006). Further improvement of spatial planning laws (Raumordnungsgesetze) and of building codes accompanied by a better information exchange between flood management authorities at the federal, state and community levels was achieved between 2002 and 2013 (Nordbeck, 2014). The coping capacities were further improved through the development of the hazard zones plans (Gefahrenzonenplan) which were implemented in more than 1500 communities by 2008 (Nordbeck, 2014). The national flood estimation and hazard mapping project HORA was initiated resulting in the regional estimation of flood probabilities for more than 26,000 km of Austrian rivers (Merz et al., 2008; Merz and Blöschl, 2008) and culminated in the mapping of potential inundation areas for the flood return periods of 30, 100 and 200 years (https://hora.gv.at). The information service went online in 2006 and received about 60,000 visitors per year on average till 2012 (Nordbeck, 2014). In Bavaria the "Action Program Flood Protection 2020" was initiated in 2001 with many measures started to be implemented only after the 2002 flood. The level of investment for the 20 year period is 2.3 billion €. The program includes newly constructed controlled retention areas mostly along the Danube and Inn Rivers, increase of natural retention, additional or rehabilitation of existing flood protection schemes, and also a diversity of flood prevention measures. For instance, a new flood protection wall with a design level of a 100 years flood had been implemented along 3.3 km in the city of Neu-Ulm (Danube) from 2005 to 2009. Investment costs: 7.1 million €. After the June 2013 flood this program has been extended (StMUV, 2014).

Event comparison in respect to riverine flood hazard

May 2013 was one of the wettest months of May in the past 150 years with around double the amount of total monthly precipitation compared to the long-term average at several locations in the Upper Danube catchment. The analysis of Schröter et al. (2015), based on the REGNIE gridded precipitation dataset (Rauthe et al., 2013) suggests that antecedent areal mean precipitation in the Danube catchment prior to the June 2013 flood was actually lower than for the August 2002 flood (110 mm in May 2013 and 140 mm in 2002). However, the likely lower evapotranspiration in May compared to the mid-summer led to the exceptionally high catchment wetness in 2013 particularly in the upstream part of the German Danube and its northern tributaries. Schröter et al. (2015) computed the areal average of the 3-day maximum precipitation during three events for the German part of the Upper Danube catchment. They amounted to 75.7 mm and 62.5 mm for 2013 and 2002, respectively. Blöschl et al. (2013) provide precipitation totals for different locations and accumulation periods, which are difficult to compare. In general, the 2002 event precipitation was centered in the northern part of the Upper Danube less affecting the alpine tributaries. Part of the precipitation during the 2013 event fell as snow in the alpine catchments and did not contribute to short-term direct runoff. However, the 2013 event was characterized by a stronger superposition of the flood waves of the Inn and the Bavarian Danube compared to the 2002 flood (Blöschl et al., 2013). This led to the highest water level in Passau since 1501, i.e. 1289 cm water level at gauge Passau (ICPDR, 2014). The peak discharge at gauge Achleiten a few kilometres downstream of Passau was 10100 m^3/s (>HQ100) (HND 2021). Partly, this is a result of the location of the center of mass of the rainfall over the quickly reacting alpine catchments and partly explained by the degree of soil saturation leading to high runoff coefficients and quick catchment response. Furthermore, a short time lag between two rainfall pulses in 2013 resulted in a single large-volume flood wave, compared to the two-peak flood wave in 2002 (Blöschl et al., 2013). In 2002, the water level at gauge Passau was 1081 cm and the peak discharge at gauge Achleiten was 7700 m^3/s (~ HQ50) (HND 2021). The return period of peak flows exceeded the 100-year return period in the downstream reaches of Upper Danube, Inn and Salzach rivers during the 2013 flood, whereas the return period flows during the 2002 flood were smaller in most part of the river network, except Naab and Regen with return periods above 100 years (Schröter et al., 2015).

Event comparison in respect to exposure

About 60,000 people were exposed in Austria to the 2002 flood and 9 lost their lives (EM-DAT, 2019). EM-DAT (2019) provides information about the exposure of only 200 people to the 2013 flood with 4 victims in Austria, which seems to be underestimated. ICPDR (2014) counts 5 victims in Austria in 2013. DKKV (2015) based on official state statistics accounts for 14 fatalities in Germany caused by the 2013 flood, whereas EM-DAT (2019) provides the number of 4 victims, which is likely not correct. However, none of the fatalities in 2013 occurred in the German part of the Danube basin (ICPDR, 2014). Thieken et al. (2016a) provides the numbers of 3 fatalities in Baden-Württemberg and 2 in Bavaria. Those probably did not occur in the Danube basin. Otherwise, this would contradict the ICPDR (2014) stating no fatalities in the Danube catchment parts located in those two federal states. Furthermore, Thieken et al. (2016a) provides the numbers for affected population and assets at the level of federal states. In total, 80,000 people were affected by the 2013 flood in Bavaria. 16697 residential buildings in Bavaria and Baden-Württemberg and additionally 129 educational facilities in Baden-Württemberg experienced inundation. However, not all of the affected people and buildings are located in the Upper Danube basin, hence, the numbers represent the upper bound estimate.

Compared to the 2002, the 2013 event hit Alpine tributaries of the Upper Danube more severely. That culminated in the highest water levels in Passau since 1501 at the confluence of the Bavarian Danube and the Inn tributary. Due to a dike breach near Deggendorf at the confluence of Isar and Danube in 2013, about 150 buildings were significantly damaged in particular due to leakage of oil tanks, and the federal motorway A3 was closed (DKKV, 2015). In August 2002 inundation occurred along the Naab and Regen Rivers (ca.30 km²).

Event comparison in respect to vulnerability

It is well-documented that awareness, preparedness and coping capacity were at a low level prior to the 2002 flood in Germany and increased significantly afterwards (DKKV, 2015). This concerns for instance the penetration rate of early warning and actionable knowledge related to early warning (Kreibich and Merz, 2007, DKKV, 2015, Kreibich et al. 2017b). For instance in 2013, only 7% of the interviewed affected population did not receive flood warning, whereas in 2002 these were 27%. In 2013, 46% of respondents were very clear about the emergency actions to be undertaken, whereas in 2002 they amounted to 14% (DKKV, 2015). Though, these results are not specific to the Danube basin, we can reasonably conclude that these figures are characteristic for Germany in general. Also in Austria significant improvement of flood risk management was achieved in the period 2002-2012 (Nordbeck, 2014). This included a proactive flood protection, integration of flood protection goals into the building codes and increased funding for flood protection, particularly in Upper and Lower Austria covering the Danube basin. Stronger priorities were set on non-structural measures for flood protection (Nordbeck, 2014). In 2013 an improvement of flood warning in terms of technical and organizational capacities was achieved in Germany compared to the 2002 flood (Thieken et al., 2016b, DKKV, 2015). In both, Germany and Austria, information and coordination capacities between the responsible authorities at and between the federal, state and community levels were improved (Nordbeck, 2014, DKKV, 2015).

Summary

In summary, the comparison of 2002 and 2013 events in the Upper Danube basin is not easy due to the fact that these events hit two countries, Germany and Austria, to different extents on these two occasions. Whereas, the German part of the Danube basin was not that severely affected in 2002, it suffered considerable damages in 2013. Overall, the 2013 event was comparable to 2002 and even more severe in terms of the resulting peak flows in the alpine tributaries (Schröter et al., 2015) and at the confluence of German Danube and Inn River (Blöschl et al. 2013). Nevertheless, the total number of victims (all in Austria) and the total economic loss were significantly smaller in 2013 than in 2002. This is in line with the previous comparison of these two events for Germany (Kreibich et al., 2017a). We attribute this impact reduction primarily to the reduced vulnerability and significantly improved flood-risk management in the period between 2002 and 2013 in both Germany and Austria. After the flood of 2002 and additionally the Alpine floods in 2005 in some mountain catchments in Austria and Switzerland (Bezzola and Hegg, 2007), the whole spectrum of structural and non-structural flood risk management measures were undertaken, such as the strengthening of flood protection infrastructure and creation of retention volumes, improvement of the legislation and building codes, improvement of communication between authorities and of early warning, increased private precaution due to increased awareness. Finally, a comprehensive flood hazard mapping was undertaken following the EU Flood Directive put into force in 2007.

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ID 16

Paired riverine flood events: 1994 and 2015 riverine floods in the Giofiros catchment (Crete) in Greece/Europe

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Short description of both events with a focus on impacts

Crete is the 5th largest island of the Mediterranean, located at the southeastern part (Figure SX.1). The island is prone to flash floods triggered by severe convective storms during late autumn to early winter (Gaume et al., 2009; Koutroulis et al., 2010, 2012; Tsanis et al., 2011, 2014). Giofiros river intersects the western part of Heraklion, the largest city of Crete. Two severe flash flood events occurred on the same day (January 13) of 1994 and 2015, causing extensive impacts, mainly over the lowland area of the catchment (Figure SX.1). During the 1994 event, the floodplain along the 11 km downstream part of Giofiros was flooded, with the maximum water level exceeding 3 m (Burlando et al., 2016). Several buildings located near the coast were flooded, leaving 49 people homeless (Koutroulis and Tsanis, 2010). Thousands of animals (sheep and cattle) drowned, over 750 acres of vineyards flooded, and damages to private properties and public infrastructure were significant (Karamanou and Rodolakis, 2006; Koutroulis et al., 2015; Perdiou et al., 2017). Monetary losses of the 1994 event are estimated at 30 million €, of which 0.6 correspond to damages at the Heraklion central wastewater treatment plant (HWWTP) that was under construction at the time (Burlando et al., 2016). Damages at the HWWTP construction site also had a severe indirect environmental impact. While numerous households were severely affected by the flood, there is no systematic record of the resulting health-related consequences.

On the same day, 21 years later, another flash flood occurred in the Giofiros river. The 2015 event was less severe in terms of rain rate but with a greater extent in terms of spatial coverage at the catchment scale. More than 80 people were rescued by boats from rooftops and flood-immobilized cars (Figure SX.2). The damage to crops, especially olives and greenhouses, livestock and households was extensive. Public infrastructure was severely affected including the damages to the HWWTP which was out of order for several days resulting to environmental impacts from untreated wastewater discharge. Business activity in the industrial zone adjacent to the river was also interrupted, causing indirect economic impacts.

Descriptions of processes between events with a focus on risk management

Over the course of the 21 years after the 1994 event, many flood risk management and socio-economic changes occurred. Following the devastating flood of Giofyros on January 13, 1994, it was clear that urgent protection measures were needed to limit the catastrophic effects of similar hydrological events. The Organization of Development of Eastern Crete, in collaboration with the Aristotle University of Thessaloniki, conducted a study perscribing specific flood protection measures in the wider area of northwest Heraklion (Ganoulis et al., 1995). During the same year, the Municipal Company of Water Supply and Wastewater Treatment conducted a second study on flood protection for the HWWTP which was highly impacted by the 1994 flash flood.

In 1995, the General Secretariat for Civil Protection (GSCP) was established. The Civil Protection Operations Centre of the GSCP (https://www.civilprotection.gr/en) coordinates and manages the provision of resources to address emergencies. The GSCP issues warnings and civil protection guidelines in the event of flooding. The operation of the GSCP provided improved resilience and coping capacity against the 2015 flood event, compared to that of 1994.

In 1994, limited protection infrastructure existed at that time, and maintenance interventions in the river channel were also limited. Due to this lack of preparedness, several bridges were overtopped by floodwater during the 1994 event. Since 2000, flood protection infrastructure was constructed in several locations along a 5 km reach upstream of the outlet of Giofiros (Figure SX.2). During the period 2001-2004, the total budget for flood protection projects was 3.2 million € (Region of Crete, 2019). Most of these projects were included in the public investment program in the frame of the forthcoming 2004 Olympic Games. During the 2015 flood event, the flood-protection dyke of the HWWTP was breached, resulting in flooding of the facilities and a pause of its operation for several days (Marias, 2015). A few bridges were overtopped.

Stream cleaning and channelisation for flood risk reduction was always an issue in Giofiros river and combined with inadequate cross-section capacity of the existing bridges and the lack of integrated flood protection infrastructure (embankments, small-scale flood prevention dams over the upstream) lead to an increase in flood hazard. In 2007, the stream was cleaned at strategic locations for the first time since the 1994 flood event. During the maintanance, over 75,000 m^3 of sediment and 3,000 m^3 of reeds were removed. Only small scale river cleaning and maintenance has taken place since 2007 at selected locations.

In the frame of the 2007/60/EC Directive on the assessment and management of flood risks, a preliminary assessment was developed in 2012 for the river basins of the water district of Crete, including the Giofiros catchment. In 2015, flood risk maps (Figure SX.2) and flood risk management plans were published (Perdiou et al., 2017), focusing on prevention, protection, and preparedness against floods. All reports, maps, and plans are available to the public through (https://floods.ypeka.gr/), facilitating increased public awareness.

Event comparison in respect to riverine flood hazard

The soils in the Giofiros catchment were saturated prior to both flash flood events. On the 13th of January 1994, and around 15:00, the intensity of the light precipitation that had saturated Giofiros soils during the previous days started to increase (Grillakis et al., 2016). At 21:00, the 5 h-accumulated precipitation reached at maximum of 123 mm (Koutroulis and Tsanis, 2010). The maximum hourly precipitation intensity recorded at the Ag. Varvara meteorological station reached 37 mm/h. The daily rain accumulation at this station reached 183 mm, exceeding the 50-yr return period levels (Figure SX.1). Daily accumulated precipitation at the catchment scale reached 108.7 mm and was mainly concentrated at the southwestern and central, higher-altitude areas of the Giofiros catchment (Ganoulis, 2003; Koutroulis and Tsanis, 2010). Daily precipitation at the Ag. Varvara was lower during the 2015 event but with a greater extent in terms of spatial coverage resulting to a catchment scale total of 78.7 mm, less than the 1994 accumulation (108.7mm), as calculated from rainfall observations obtained by automatic weather stations (Lagouvardos et al., 2017). Maximum hourly precipitation intensity recorded in Metaxochori meteorological station was 15.8 mm/h.

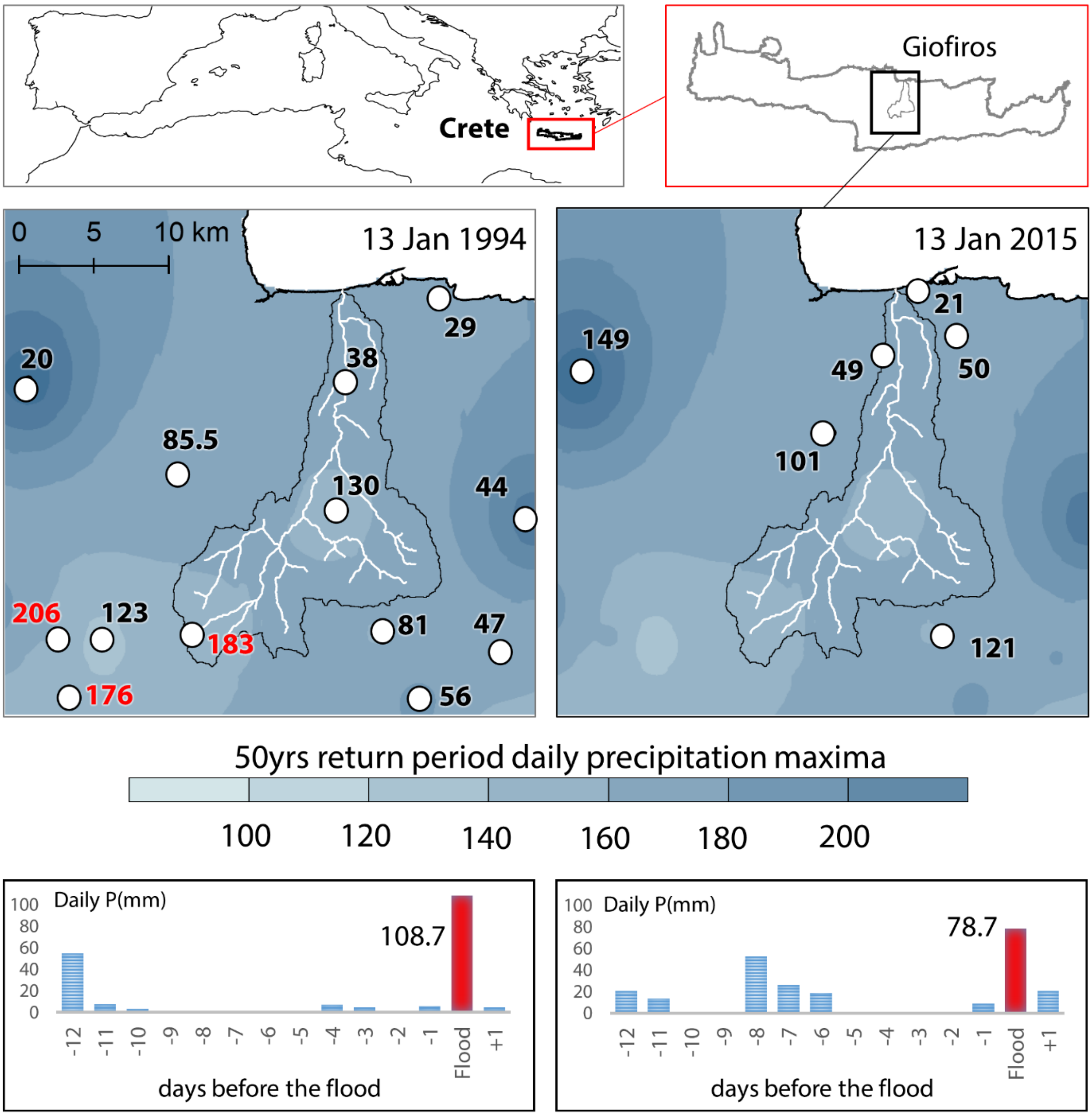

Figure SX.1: Overview of the 1994 (left) and 2015 (right) flood events in respect to return periods. Point values correspond to daily precipitation accumulations for each event. The underlying color areas correspond to spatially interpolated (IDW) rainfall with 2% Annual Exceedance Probability (return period of 50 years) using GEV based on long term precipitation records of 52 stations. Values marked in red denote the exceedance of the event scale daily precipitation in respect to the 50-yr precipitation. Lower panels denote the basin scale average daily precipitation before the flood events.

The synoptic meteorological prevailing background conditions of both events favor for heavy, localized rainfall. On January 13, 1994, a frontal depression in south-east Mediterranean moved eastward and north crossing the island of Crete. This low pressure area deepens to 1007 hPa centered just south of Crete (animation file 1994MSLP) producing high precipitation over central Crete and the flash flood of Giofiros basin (Iordanidou et al., 2016, 2015). A similar atmospheric pattern evolved during the 2015 event. In this case, the depression originated from northwest, crossed the island Crete and remained over the eastern part from more than one day, continuously deepening until its dissipation. Both systems are characterized by low propagation velocities with prolonged persistence over the affected area, allowing for high precipitation accumulations.

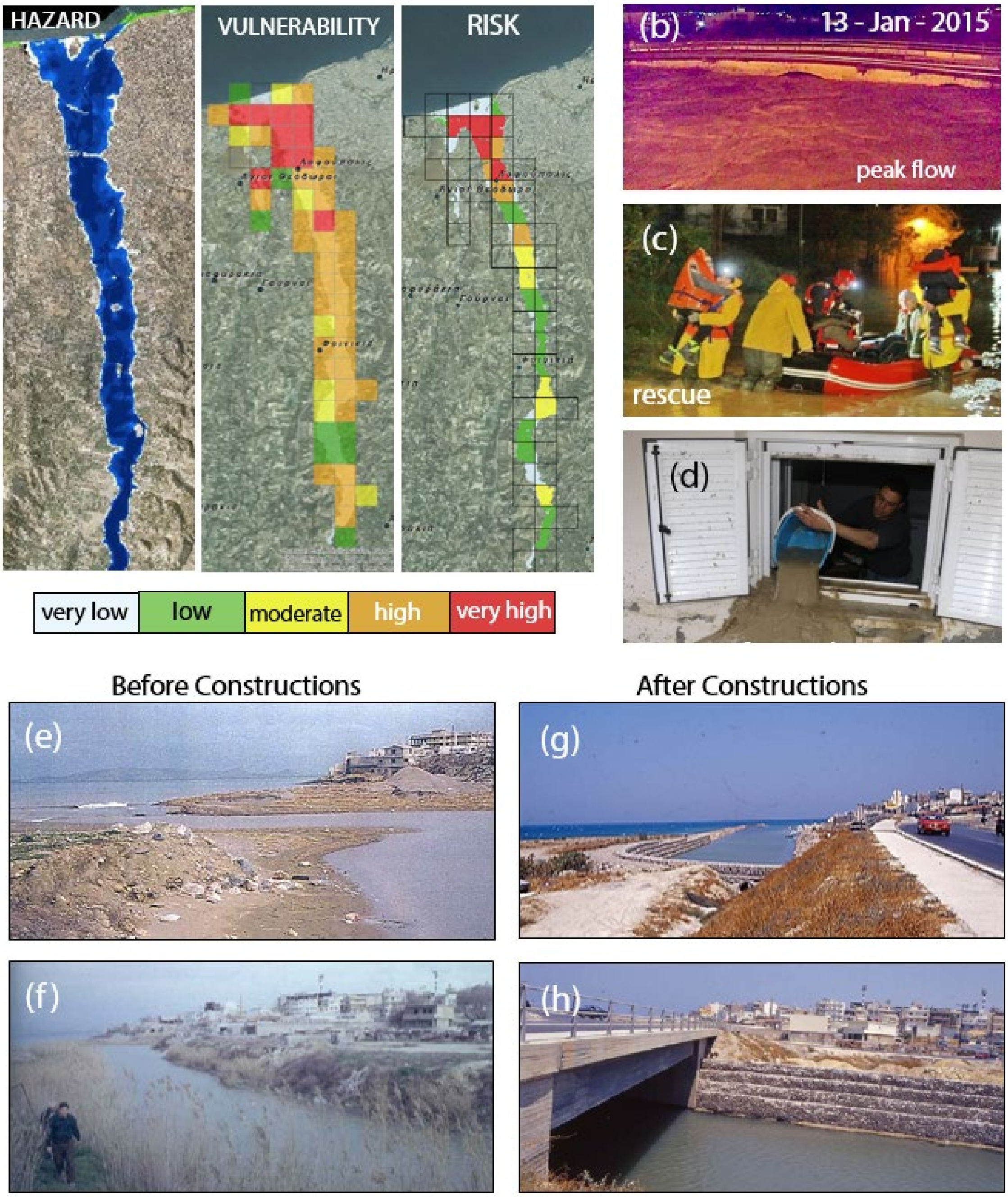

Figure SX.2: Left: Flood hazard, vulnerability and risk maps for T=50yrs return period event (Perdiou et al., 2017). Right: Photos during (b, c) and after (d) the 2015 event. Lower panels: photos close to the outlet of Giofiros river before (e, f) and after (g, h) constructions (Karamanou and Rodolakis, 2006).

In terms of flood peak discharge (about 300 m^3/s) both events are classified in the order of 2% annual exceedance probability (50-yr return period (Koutroulis et al., 2010; Region of Crete, 2019)). Inundation depth was higher for the 1994 event due to the lack of flood protection infrastructure that were constructed along a 5-km reach upstream of the outlet of Giofiros river after 2000.

In terms of the overall flood hazard assessment for T = 50 years of peak discharge (Figure SX.2), 66.7% of the potential flood hazard zone is characterized by very low risk, 17.1% by low, 6.7% by moderate, 4.8% by high and 4.8% by very high risk.

Event comparison in respect to exposure

The presence of unlicensed structures and settlements on the riverbanks and the high residential density over riparian areas are the main factors with respect to exposure for both events, but in a different degree for each one of them. The number of inhabitants of the city of Heraklion according to the 1991 census was about 115,270 people. Within 20 years (2011 census), the population increased by a factor of 22% (140,730 people), and lead to the expansion of residential and industrial activities in flood-prone areas around the Giofiros river and the increase of the number of risk-exposed people over time. However, major developments in flood protection constructions at the lowland flood-prone areas since 2000 contributed to the reduction of the exposure. I As a result, the impact of the 2015 event was lower, even though at least 11,000 people and an approximate number of 5,000 buildings were inside the area classified as very high exposed (Figure SX.2). Local media websites report that during the night of 14th of January 2015, 80 people in total were rescued, a total of 120 houses were significantly affected and at least 50 businesses located at the industrial zone close to the river were severely affect and applied for disaster recovery assistance, (ekriti, 2018, 2015; haniotika-nea, 2015).

Event comparison in respect to vulnerability

Despite the fact that information is not reliable for the 1994 event, it is likely that awareness and preparedness was low. People affected were likely aware of the eminent flood risk due to a preceding event that took place on 1985 but were did not expect this severity. The fact that the 1994 event evolved during midnight and the quick response time of the catchment (3.4 h (Koutroulis and Tsanis, 2010) made things worst. At the time, river channel maintenance was not implemented at a regular basis and as a result, forest debris accumulated in the river bed and decreased the transport capacity of the stream. Although several studies of potential flood protection measures existed before the 1994 flood, only few of their measures were implemented. At the time, the civil protection service had not been established, so the crisis was managed by local authorities and the Fire Service. Several buildings and properties were unlicensed, and therefore private or public insurance claims were not due. The early warning was based on the limited forecasting capacity of the means of this period and the emergency management was less effective compared to that of the 2015 event, where management was undertaken by the civil protection service in collaboration with the Hellenic Fire Service through the Unified Operations Coordination Centre (UOCC). Furthermore, experience from the 1994 and other less severe flood events increased awareness. The General Secretariat for Civil Protection organized information campaigns and published self-protection guidelines (Civil Protection Service, 2010) communicated to different audiences for awareness raising. Public events organized in the frame of research projects on floods contributed on awareness increase (Borga et al., 2011; Burlando et al., 2016; Tsanis et al., 2014).

In 2015, the Hellenic National Meteorological Service (HNMS) issued a severe weather warning that was communicated to the public by the local media. Local amateur weather networks contributed to the enhancement of the public awareness and preparedness. The operation of the civil protection service provided improved organizational and management capacity during the 2015 event. Regarding public flood insurance claims by individuals and businesses, these are due upon damaged property inspection by the authorities, after application for disaster recovery assistance (Perdiou et al., 2017). Nevertheless, this process is time-consuming and by the end of 2018 insurance claims for the 2015 event were yet to be handled (ekriti, 2018). In general, the coping capacity in 2015 was higher due to the reduced vulnerability stemming from organizational improvement and risk awareness.

Summary

Despite the increase in exposure, the lower damages from the second event were due to a combination of factors of reduced hazard and decrease in vulnerability. The reduction in exposure came as a response to the sudden catastrophic event of 1994 that gave a strong push for action towards flood mitigation. This event triggered a series of actions that lead to the construction of critical flood protection infrastructure contributing to the reduction of the exposure to flood risk. Socio-economic developments and advancements in risk management fueled by organizational improvement and technological developments (improved forecasts, easier and more effective communication, and availability of information) lead to the decrease in vulnerability in the case of the second flood event that took place in 2015.

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ID 17

Paired riverine flood events: 1998 (event-year1) and 2016 (event-year2) riverine floods in the the Sukhona river basin (Veliky Ustyug, Vologda oblast) in Russia/Eurasia

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Short description of both events with a focus on impacts

Ice jams on the rivers in European Russia cause the greatest damage in the period of ice phenomena. Congestion of ice in channels results in a sharp rise of water level, often flooding. Ice jam floods are particularly dangerous because they occur in cold seasons and are accompanied by ejection of ice on the shores that breaks structures located within the flood zone. The damage caused by ice jams typically far exceeds the damage caused by floods during the ice-free period. In addition to flooding and damaged hydraulic structures, prolonged ice jam delays the cleaning of the river of ice, reducing the navigation period.

The lower course of the Sukhona river is the most problematic area in the north of European Russia There are powerful ice jams form during breakups practically every year in this region. The major ice jams are often 10–20 km in length, and their lifetime ranges from several hours to 3–5 days.

Two ice-related floods were chosen for comparison: 3–5 May 1998 and 15–19 April 2016. Both events were observed in the lower reaches of the Sukhona River, near the city of Veliky Ustyug. The number of affected people was 8 000 in 1998 and 7400 in 2016. Several thousand buildings were destroyed. Official calculations of direct economic impacts (monetary damage) are given in the table. To account for inflation (rising prices) the values are translated into US$: ~ US$ 44 000 000 in 1998 and ~ US$ 7 500 000 in 2016.

Descriptions of processes between events with a focus on risk management

Since 1998, there have been important changes in flood risk management in the region. With the support of the Vologda region, the conditions of ice jam formation were researched. After the 1998 flood, the volume of preventive measures has increased significantly. Ice cutting, blasting, and surface treatments have been carried out annually since 2000. Operational information on water levels is becoming more accessible to residents. To attract investment, the tourist project "Veliky Ustyug - the birthplace of Father Frost" was started. This is due to the economic development of the region and attracting attention to the problem of flooding. Unfortunately, at the moment there are no official approved boundaries of the flood zone within the city and its surroundings. Construction in the flooded areas continues and there are no resettlement programs for residents from these areas. Residents who do not have other living places reconstruct their houses after floods. The price of land plots in the flood zone is lower. There are no ban to build new houses in this zone.

Event comparison in respect to riverine flood hazard

In 1998 and 2016, very high water levels were observed. But the hydrometeorological conditions of the formation of the ice jam flood differed. In 1998, due to the long and severe winter very thick ice cover formed. Large volumes of ice material and high water discharge contributed to the formation of a catastrophic ice jam. In contrast to 1997-1998, the winter of 2015-2016 was relatively warm. Because of the mid-winter breakup in December 2015, a hummocky ice cover was formed. In winter the bed of the river Sukhona was filled with frazil[1] ice. Rainfall during breakup also contributed to high water levels in 2016. The figure shows the change in water levels in the spring of 1998 and 2016.

In 2016, a wooden ice control structure was constructed 40 km upstream from the city. According to social media, the destruction of the structure occurred immediately after the start of the breakup. According to official data, the ice control structure helped to stop the ice run and the experience was recognized as successful. But only general recommendations of experts were used in the construction of the ice control structure. The calculation of parameters was not completed. In our opinion, in the conditions of 2016, the structure would not have been able to prevent flooding.

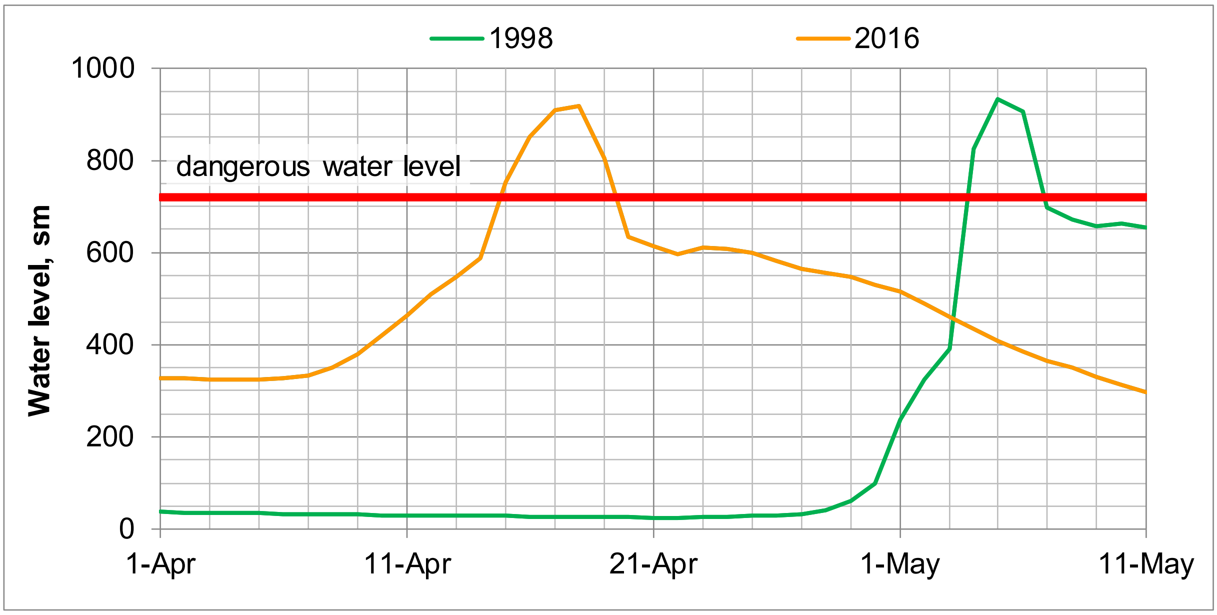

Fig. 1. Water levels on the Sukhona river at Velikiy Ustuyg in the spring of 1998 and 2016

Event comparison in respect to exposure

In both cases, the flood area is 12 000 ha (affecting the same locations), roads, communication and power lines, schools and other social objects were exposed. Compared to 1998, the number of buildings exposed and of people exposed decreased in 2016. This is due to a decrease in the total population in the city and in flooded areas.

Event comparison in respect to vulnerability

Veliky Ustyug has been exposed to ice-related floods since its foundation. Disastrous floods were observed here in 1903, 1906, 1929, 1936, 1953, 1979, 1991, 1998, 2013 and 2016. The water level forecast was made 1-4 months before the breakup. In 2016, preparations for a dangerous flood began in December 2015. Existing forecasting methods are quite accurate and reliable. In 2016 elderly people and bedridden patients were evacuated in advance.

[1] Also known as shuga, slush ice. In the turbulent, faster moving portion of the river, where the flow is well mixed, ice is created in the form of frazil ice particles. These are small discs of ice ranging in size from less than 0.1 mm up to a few mm in diameter.[F. Hicks, 2016 An Introduction to River Ice Engineering for Civil Engineers and Geoscientists]

Property insurance is not very popular. But after catastrophic floods, the state pays monetary compensation. The attitude of residents to floods does not change. In 2016, drinking water and food were brought to residents of flooded homes. After the floods, residents are waiting for cash payments from the state. In 1998 reactive measures included only blasting, in 2016 icebreakers and bombing from the air were also used. In 1998, official operational information on flooding wasn't enough. In 2016, operational information was reported on radio, television and the Internet every hour. Social media helps to spread official operational information. The population used this information. Some residents went to live with relatives or temporary housing, and raised furniture to the upper floors. But many people are usually afraid to leave their homes. In 2016, residents collected information about flooding and made a real-time map of the flooding.

Summary

Ice jam floods are observed on the Sukhona River every 4 years. Since 1998, there have been important changes in flood risk management in the region. Preventive measures are carried out annually; the warning system has improved. In 2016, operational information was reported on radio, television and the Internet (social media) every hour. In 1998 there were no regular announcements for the public. However, there are no official approved boundaries of the flood zone within the city. Construction in the flooded areas continues and there are no resettlement programs for residents from these areas. The population is attracted by the low price of land plots and the government's promise to build a protective dam that will solve the problem of flooding.

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Announcement of the sale of land plots. The village of Dymkovo, right bank of the Sukhona river, opposite the city of Veliky Ustyug. April 2016. (“Land plots for individual housing construction are sold here”)

ID 18

Paired riverine flood events: 2002, 2007, and 2013 riverine floods in Jakarta, Indonesia

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Since this report covers three events, it is identical to report of ID 4, please see pages 19-24.

ID 19

Paired coastal flood events: 2016 and 2017 coastal floods in Charleston city in South Carolina, U.S.

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Short description of both events with a focus on impacts

Charleston is the largest city in South Carolina, is the 24th fastest-growing U.S. metro area, and is one of the cities in the US most vulnerable to coastal flooding due to storm surge in terms of losses to residential, commercial and industrial properties (Strauss et al., 2012). The sea has already risen about a 0.3m in the last 80 years off South Carolina, causing regular flooding in downtown Charleston. Moreover, Charleston has been periodically affected by hurricanes and tropical storms (Peng et al., 2006). Just recently, two severe storm surge events have occurred in 2016 and 2017 leading to severe damages. In October 2016, the tidal level Charleston recorded its third highest level ever due to the Hurricane Matthew (Stewart, 2017), exceeded only by Hurricane Hugo in 1989 and by an unnamed hurricane in 1940. Based on an insurance report (AON, 2017), in South Carolina a 2.0 billion USD water-related damage was recorded, thousands of homes and businesses were damaged or destroyed, and five people died. The following year, the Hurricane Irma generated one of the highest storm surges, higher than the one experienced during the Hurricane Matthew of 2016. However, reported damage was significantly lower and two people were killed in South Carolina (AON, 2018).

Descriptions of processes between events with a focus on risk management

The persistent sea level rise and disastrous consequence of Hurricane Hugo in 1989 (Category 4 storm) have driven local and national authorizes to improve their early warning systems and emergency protocols and build more reliable structural measure against storm surge (e.g. seawalls). Nonetheless, the reason behind the lower fatalities and economic losses occurred during Irma (2017) can be associate to different reasons. From the one side, the different spatio-temporal distribution of the two hurricanes and their trajectories may have influenced the fatalities and economic losses in Charleston. From the other side, the higher damage occurred during Hurricane Matthew can be due to failure of seawall and to the high number of people that did not evacuate the Charleston area (Horney, 2016; Marchant and Cope, 2016). In fact, Horney (2016) showed that in Charleston about 50% of the residents under evacuation orders actually left their homes. In South Carolina, an evacuation was called for 1.1 million people (Post and Courier, 2017a). Multiple factors can influence the decision of not evacuating. Among them, the previous disaster experience and risk perception play a crucial role (Dow and Cutter, 1998; Kang et al., 2007; Horney et al., 2010). In fact, many people lost their memories of the disaster because no severe hurricane was experienced in nearly 10 years. Moreover, as the AON (2017) report described "*Several communities, including areas between Charleston and Columbia, were still in the midst of recovering from damage sustained during the historic floods in October 2015 that left considerable infrastructure damage and weakened dams and levees*". On the other hand, the lower damages experienced with Irma can be found in the higher awareness and preparedness level due to the short time occurred between two powerful hurricanes as Matthew and Irma (which allow the population to keep a high-risk perception). Another reason for such higher preparedness can be found in the fact that the Irma track was predicted to be closer to Charleston than the occurred one (Post and Courier, 2017b). Moreover, the lower damage experienced with Irma could be due to the reliability of the protection measures (e.g. dunes rebuilt 5m high in Edisto Beach) installed after Matthew (abc4news, 2017a).

Event comparison in respect to coastal flood hazard

The coastal flooding occurred in Charleston on October 2016 was mainly due to high storm surge produced by the Hurricane Matthew, a Category 1 hurricane when made landfall (first one since Hurricane Hazel in 1954) in South Carolina. A combination of both storm surge and wind caused extensive damage along the coastline of South Carolina (NWS, 2017). In particular, a total rainfall amount of about 260mm between the 7th to 9th of October 2016, with a wind gusts of 112km/h was recorded at Charleston (see Figure 1) (NWS, 2017). An extensive storm surge and tidal level were recorded in Charleston with a level of about 1.88m and 2.83m, respectively, at Charleston Harbor Tide gauge (NWS, 2017). The extreme storm tidal level was the third highest ever recorded in Charleston, exceeded only by Hurricane Hugo in 1989 that produced a record storm level of 6.2m along the offshore part of the coast to the entrance to Charleston Harbor (Hollifield and Lackey, 1989; Guimaraes et al., 1993; Peng et al., 2006; AON, 2017). A failure of a seawall occurred near Charleston. However, intense beach erosion was reported on Edisto Island causing damages on 70 homes and roads were covered with up to 1.5m of sand (NWS, 2017).

The following year, the powerful Hurricane Irma hit Charleston causing sever coastal flooding and damages. Hurricane Irma mainly affected north eastern Caribbean and the Florida Keys, while its remnants would later spawn heavy rains in parts of Georgia, South Carolina, Alabama, Tennessee and Mississippi before finally dissipating (AON, 2018). Despite the fact that the track of Hurricane Irma was not as close and parallel to the coast of South Carolina as the one of the Hurricane Matthew (see Figure 1; Martin et al. 2020), the storm brought significant wind gusts near hurricane-force to coastal area, rainfall and flooding (AON, 2018; Cangialosi et al., 2018). In fact, even tropical cyclones that approach from the Gulf of Mexico and pass over land can have significant impacts in Charleston (Lindner and Neuhauser, 2018). Even if Irma did not directly make landfall in South Carolina like Matthew, a total rainfall of 225mm, between the 10th to 12th of September 2017 (Figure 1), and a wind gusts of 96km/h were recorded in Charleston (Elis and Román-Rivera, 2019). In terms of storm surge, Hurricane Irma exceeded the Matthew's storm tide, recording a storm tidal level of about 3.02 m (storm surge 1.48m) at Charleston Harbor Tide gauge (Cangialosi et al., 2018). From Figure 1, it can be seen that Irma slightly exceed Matthew also in terms of coastal flooding in the city of Charleston. As in case of Matthew, no dyke failure was recorded during the coastal flooding with Hurricane Irma (AON, 2018).

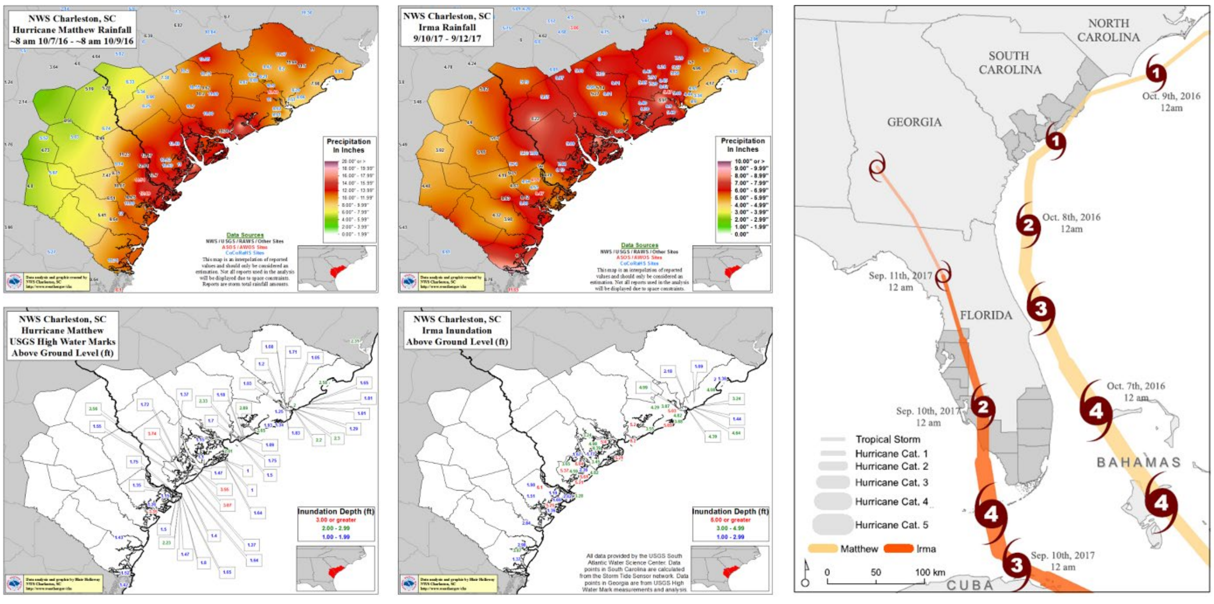

Figure 1. Rainfall (first row) and inundation levels (second row) occurred during the Hurricane Matthew and Irma (second column) (adapted from NWS, 2016; 2017; Martin et al., 2020).

Event comparison in respect to exposure

In the past, Hurricane Hugo generated a total economic loss of about 3.0 billion USD and 27 fatalities. Both events of 2016 and 2017 had important implications on the number of affected people and economic damages in Charleston city and across the whole state of South Carolina. In particular, 5 deaths and 2.0 billion USD of economic damages due to the Hurricane Matthew in 2016, while 2 deaths and minor economics damages were due to the Hurricane Irma in 2017 across the South Carolina state. Moreover, at least 800,000 and 250,000 homes and businesses lost power access during Matthew and Irma respectively (Stewart, 2017). Several counties were affected during Matthew and Irma (Stewart, 2017). A total of 115,401 and 22,897 insurance claims, and 878,080,727 USD and 120,442,782 USD incurred losses were reported after the Hurricanes Matthew and Irma respectively in South Carolina (South Carolina Department of Insurance, 2018).

In Charleston, coastal flooding was extensive during Hurricane Matthew of 2016. In particular, many communities were still recovering after the severe floods of October 2015, which weakened many dykes and hydraulic structures (AON, 2017). Consequently, a seawall near Charleston breached as exposed to intense rainfall and gusty winds. The flooding filled many downtown streets with water, with a consequent overflow of the seawall along East Battery Street at edge of the city. An additional issue due to the severe flooding was the black water of first floors joining the water in the street (AON, 2017). About 140 roads in Charleston were closed, about 10500 power outages were registered in Charleston county by SCE&G (Abc4news, 2016), and more than 175000 people were exposed. Besides the damages in Charleston, the area in South Carolina that was affected the most by the storm was Hilton Head Island (south of Charleston), where 3,724 homes and buildings (19% of the total number of structures) were damaged or destroyed (AON, 2017) due to flood inundation or fallen trees. Severe beach erosion was reported from Isle of Palms and Edisto Island, with at least 70 homes damaged. Elsewhere, the Emergency Management Division in Florence County (near Myrtle Beach) cited that 2,324 structures were affected.

Despite for the higher storm surge level reached with the Hurricane Irma in 2017, the consequences in terms of affected people and economic losses were lower than the ones achieved with Matthew. The difference in economic losses could be due to the fact that after Hurricane Matthew structural measures were regularly maintained and that preparedness was higher as the expected forecast showed a path closer to Charleston then the one occurred. More than 150000 people were exposed. Coastal flooding due to Irma damaged many homes and businesses, forcing the authorities to close 111 roads (AON, 2018) and registering about 15000 power outages in Charleston county by SCE&G (Abc4news, 2016). However, the flooding caused only minor economic losses in downtown Charleston and surrounding areas within the tidal zone after Hurricane Irma (AON, 2018). Damages due to storm surge were reported on Fripp Island and other coastal areas like Folly Beach. Severe beach erosion occurred in Hilton Head, and Beaufort (Cangialosi et al., 2018). In Charleston, Hurricane Irma prompted an 11.3% year-to-year decline in occupancy, while Hurricane Matthew caused a 5% drop in 2016 (Post and Courier, 2018).

Event comparison in respect to vulnerability

After Hurricane Hugo, which was used as benchmark to measure the severity of other hurricanes, collaborations between local and state agencies were significantly improved, bringing to better tools for officials track evacuations, damages and outages (Greenville, 2018). Flood mitigation programme and messaging systems (including a new mobile app was developed by the state's Emergency Management Division) for communicating flood emergency and preparedness were improved. Moreover, also the promotion of education programme on hurricanes and flooding was improved.

Tropical storm warnings and evacuation orders were regularly issued for both Hurricane Matthew and Irma for the South Carolina (Cangialosi et al., 2018) by the National Hurricane Center and by the Governor respectively. Most likely, these warnings contributed to decrease casualties, people affected and economic losses. The South Carolina Emergency Management Division, was the coordinating agency responsible for the state-wide emergency management program including disaster preparation (e.g., emergency plan), monitoring the evolution of the Hurricanes, and recovery (e.g., mitigation activities) phases during both Matthew and Irma. Disaster recovery centres were opened in North Charleston to help residents with damages and losses from Hurricane Matthew. A total of 8 shelters in operation, 3,146 totals sheltered, 393 average sheltered people per night, and 1560 maximum sheltered was recorded for Charleston county during Hurricane Matthew (South Carolina Disaster Recovery Office, 2017).

Despite the similar non-structural measures implemented after Hurricane Hugo, the event in 2017 caused significantly lower damage compared with the one in 2016. As reported by Post and Courier (2017b) "*Folly Beach suffered worse erosion than it did during Hurricane Matthew. Edisto Island's main road was completely submerged in sand Tuesday, but officials found the damage overall to be less extensive that what the island experienced during Matthew*". One possible reason of the lower damages recorded in the event of 2017 could be connected to the different awareness and preparedness after Hurricane Matthew. In fact, as reported by Abc4new (2017b), Charleston's Mayor John Tecklenburg stated that the city given out 20000 sandbags in preparation for the Irma storm, which was the highest number of sandbags ever recorder if compared to a previous one of 15000 (Post and Courier, 2017b). Fortunately, the storm tracked through Florida and Georgia, 200 miles away from Charleston as predicted (Post and Courier, 2017b). Also during Hurricane Irma, information on how to prepare for a hurricane were disseminate to the population and early warnings were issued (Post and Courier, 2017b). No other evidence of increased awareness and preparedness were found.

Summary

Two consecutives coastal flooding occurred in Charleston, South Carolina, in 2016 and 2017 as consequence of two powerful hurricanes, Matthew and Irma. Whereas, both hurricanes brought severe precipitation and wind gusts, Hurricane Irma caused higher storm surges in Charleston. Unlike Matthew, which impacted most of South Carolina, Irma's worst impacts appeared to be on the coast. However, the people affected and economic losses were considerably lower during Irma than Matthew in Charleston. On the one hand, the lower damages can be due to the different coastal flood hazard generated by diverse spatio-temporal hurricane characteristics. On the other hand, breached seawall during Hurricane Matthew and additional structural measures implemented after 2016 may have also contributed to reduce flood damages in the event of 2017. Moreover, preparedness levels and disaster memory between Matthew and Irma may have played an important role in the lower economic losses and fatalities. This case study shows how two similar consecutive events can generate different damages due to the different levels of preparedness of the population and to the failure of protection measures built to protect urbanized areas after a disastrous event (safe-development paradox, Kates et al., 2006).

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ID 20

Paired coastal flood events: 2007 (Sidr) and 2009 (Aila) cyclone and storm surge in Coastal Areas in Bangladesh

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Short description of both events with a focus on impacts

In Bangladesh, four major types of flooding are evident: fluvial; tidal; fluvio-tidal floods; and storm surge (Haque and Nicholls, 2018). Among different types of flooding, the coastal area of Bangladesh has a long history of severe damage and disruption due to cyclones and associated storm surges (Alam and Collins, 2010). The severity of cyclonic storm surge largely depends on the following factors: wind speed, tidal condition, location and timing of landfall. Cyclones and associated storm surges can breach embankments threatening life and livelihoods on the coast. Here, we compare two coastal flooding events that occurred due to cyclone induced storm surge. The Cyclone Sidr in 2007 and Aila in 2009 are two recent storm surge events which resulted in severe damage and prolonged human suffering (Haque and Jahan, 2016; Sadik, Nakagawa, Shaw, *et al.*, 2018). The main characteristics and track of the two cyclones are shown in Figure 1. Cyclone Sidr made its landfall on the southcentral coastal area on November 2007 with minimum sea level pressure 944 hPa and maximum sustained (three minute) wind of 240km/h. It mostly affected south central and partially the southwestern zone of Bangladesh with a maximum surge of 4.16 m (Adnan et al. 2019) plus low tide (ERD, 2008). Cyclone Aila made its landfall on the coast of west Bengal of India with 974 hPa minimum sea level pressure and 120km/h maximum sustained (three minute) wind. It mostly affected the south-western part of Bangladesh with a maximum surge of 4.10 m (Adnan et al. 2019) plus high tide (UNDP, 2010). In both cases, storm surge flooded an area of the 11 south-western and south-central coastal districts by overtopping and breaching coastal embankment system which affected millions of people by damaging their houses, thousands of kilometers of roads and embankments, educational institutions, and rural infrastructures (ERD, 2008; Sadik *et al.*, 2019). Both cyclones 'Sidr' and 'Aila' affected Bangladesh and India, but for the paired event comparison, only the damage in Bangladesh is considered. The storm surge of cyclone Sidr (2007) caused 4,407 dead and missing and 55,282 injured (ERD, 2008). Direct economic impact was 1,158 million USD (ERD, 2008) in 2007 values (up-scaled and converted to 1,329 million USD/930 million EUR as at 2009). Additionally, indirect loss of 516.9 million USD was caused (ERD, 2008) as well as intangible impacts such as rise in mental health related problems (Kabir et al., 2016) and damage to the Sundarbans, which is a World heritage site (ERD, 2008). In comparison, cyclone Aila in 2009 caused 190 dead and missing and 7,100 injured (UNDP, 2010). Direct economic impact was 269.28 million USD (Xinhua, 2009) (converted to 188 million EUR). Severe intangible damage (much higher than after cyclone Sidr) was caused since a large number of people were displaced or migrated. In several areas, people could not return for 3~4 years due to continued tidal flooding. A large number of people changed their livelihoods to daily labor or fishing to cope (Kumar Paul, 2013; Abdullah et al., 2016). This change in livelihood had extreme impacts on their culture, standard of living and social status.

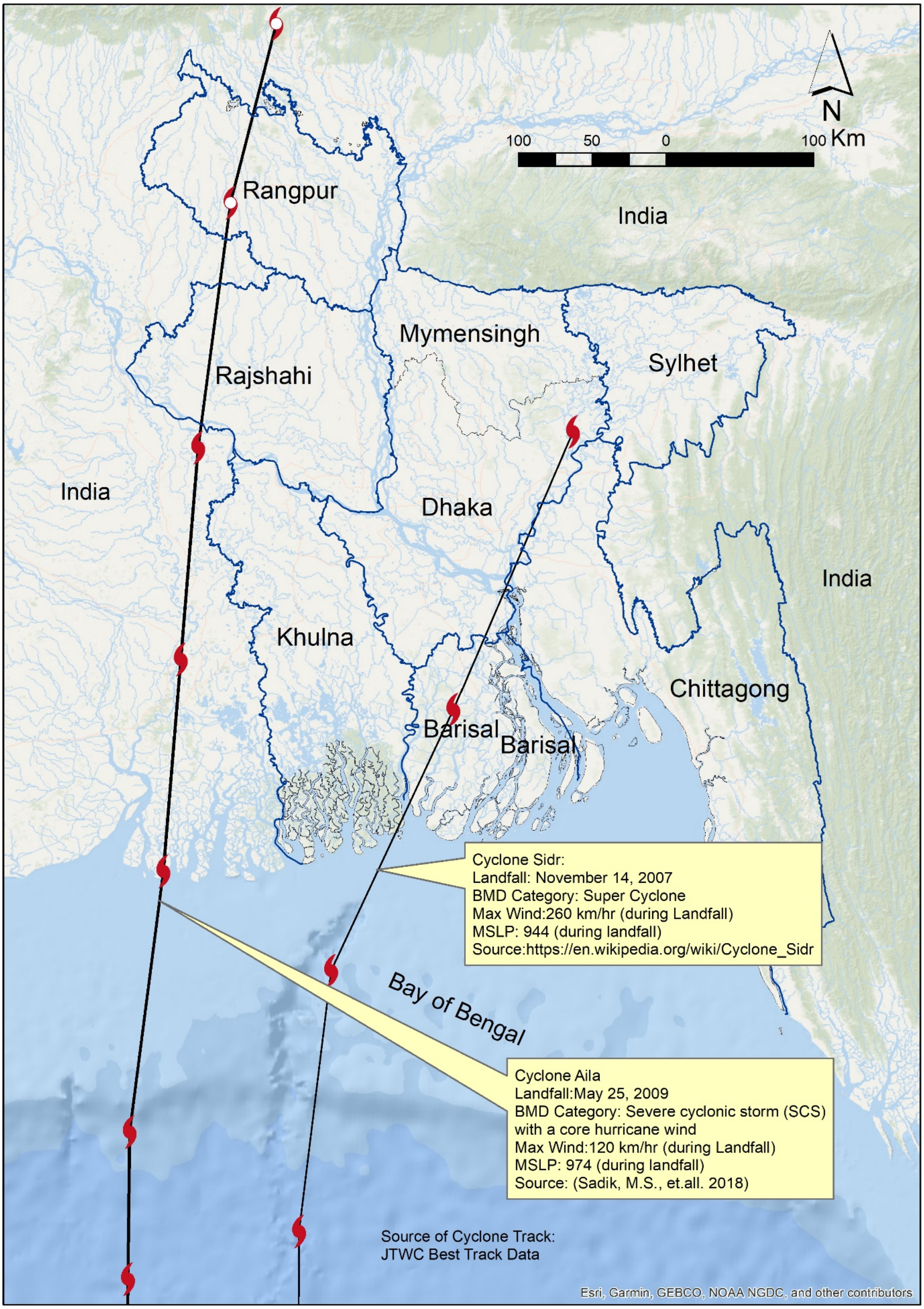

Figure 1: Track of Cyclone Sidr (2007) and Aila (2009)

Descriptions of processes between events with a focus on risk management

The Cyclone Sidr 2007 appeared at a time when the Government was making a paradigm shift in disaster management putting more focus on preparedness and emergency response capacity through a nation-wide comprehensive disaster management program (Kirsten and Uddin, no date). Taking the lesson from Cyclone Sidr, the government and international NGOs increased their capacity to act more effectively during emergency by pre-stocking of food and non-food emergency supplies. After Cyclone Sidr, ~1,150 million Euro were invested in humanitarian aid, emergency reconstruction and rehabilitation (Ozaki 2016). Moreover, trainings were provided to local volunteers in several places for improving risk communication. The government realized that rehabilitation and reconstruction of coastal infrastructure i.e. rural roads, cyclone shelters, coastal polders were necessary (ERD, 2008). However, at the time of Ailas impact in 2009 this program was yet to start. In the time period between Cyclone Sidr and Cyclone Aila, government and NGOs achieved an improved community consciousness on disaster risk in terms of disaster awareness. Actions in response to increased awareness (precaution, evacuation behaviour, emergency measures, etc) were improved (Parvin et al., 2019). However, long term precaution was not improved (Paul and Routray, 2013; Parvin *et al.*, 2019). Another major change in between Cyclone Sidr and Cyclone Aila was improved capacity of post-disaster response and recovery. However, this change was not enough to ensure effective recovery. The recovery after Aila was slower than before (IRIN, 2009; UNDP, 2010; Sadik, Nakagawa, R. Rahman, et al., 2018). Therefore, several researches highlighted the need of further improvements by adopting a comprehensive recovery program, inclusion of build back better principle, and risk-informed decision making, at the time of Aila recovery (Nadiruzzaman and Paul, 2013; Mallick and Islam, 2014). The National Disaster Management Plan 2010-2015 which was prepared after cyclone Aila also stated the need of comprehensive response and recovery. Such policy changes based on realizing the need of comprehensive recovery and long term DRR measures was an improvement in disaster risk management (Sadik, Nakagawa, M. R. Rahman, *et al.*, 2018; Sadik, Nakagawa, R. Rahman, *et al.*, 2018).

Event comparison in respect to coastal flood hazard

In terms of wind speed cyclone Sidr was a super cyclone as per the Bangladesh's classification of tropical cyclone intensity (Debsarma, 2009) which is equivalent to category 4 of Safir-Simpson hurricane wind classification. At the time of landfall, the maximum three minutes sustained wind was 240 km/h and the minimum sea level pressure was only 944 hPa. Fortunately the prevailing tide was low-tide (ebb tide) which had lowered the water levels due to non-linear interaction (ERD, 2008; Hussain *et al.*, 2017). The resulting observed storm surge was 4.16m surge (Adnan et al. 2019) plus low tide (ERD, 2008).

In terms of wind speed cyclone Aila was much weaker but the storm surge was similar. Cyclone Aila was a severe cyclone with core hurricane wind as per the Bangladesh's classification which was equivalent to a category 1 hurricane (Sadik, Nakagawa, R. Rahman, *et al.*, 2018). At the time of landfall, the maximum three minutes sustained wind speed was 120 km/h and the minimum sea level pressure was 974 hPa. Unfortunately, the landfall time coincided with high tide (flood tide) which had increased the water levels. The storm surge was 4.10 m (Adnan et al. 2019) plus high tide (UNDP, 2010, UNDP *et al.*, 2013; Debsarma, Rahman and Nessa, 2014).

In this region, storm surge is the key control of cyclonic damage due to the characteristics of the coastal processes in the Bay of Bengal (Khan et al., 2021). These include: (i) high tidal range (as high as 5 m) along with tide-surge interaction as shown in Figure 2; (ii) location of coastal area below 5 m above mean sea level; (iii) recurvature of tropical cyclones; (iv) shallow continental shelf; and (v) the triangular shape at the head (Khan et al., 2021; Murty et al., 2017; Murty and Flather, 1994). There are also other areas around the world where storm surges are more relevant than wind speeds (Camelo and Mayo, 2021).

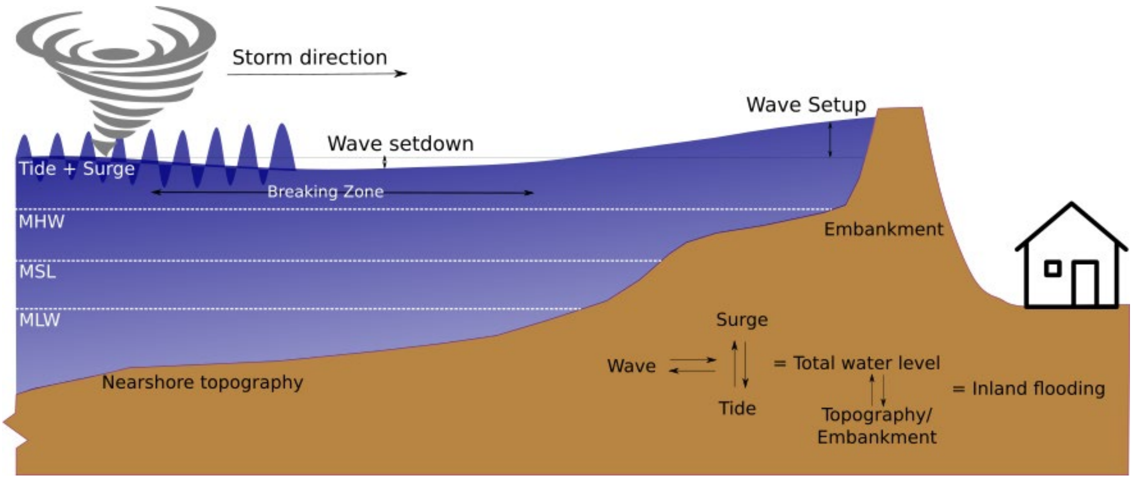

Figure 2. Conceptual diagram of the involved processes that determine the water level evolution and its interaction with the controls determining the inland flooding (Source: Khan et al. 2021).

In both cases, coastal dykes were overtopped and breached. Cyclone Sidr washed away around 362 km coastal embankment (ERD, 2008) and Cyclone Aila washed away 237 km of coastal embankment (UNDP, 2010). However, the recovery of coastal embankment after Cyclone Aila took a longer time which resulted in repeated tidal flooding for 3 years in some affected areas (Walton-Ellery, 2009; Sadik *et al.*, 2019).

Event comparison in respect to exposure

In both cases the south central (Barishal) and south western (Khulna) coastal region of the country were exposed to the cyclones. The landfall for Sidr occurred in the south-central coast of Bangladesh, while the landfall for Aila occurred 90 km west of Bangladesh (mainly in West Bengal of India). Therefore, Cyclone Sidr mostly affected the south-central region whereas the Cyclone Aila mostly affected the south-western part of Bangladesh. Still, in both cases, the Sundarbans mangrove forest, Mongla port and the coastal towns of Khulna and Borishal division were highly exposed. 18.7 million people were exposed in 2007 (ERD, 2008), while only 3.9 million people were exposed in 2009 (UNDP, 2010).

Event comparison in respect to vulnerability

Vulnerability of coastal communities and cities was always high, to cyclone and storm surges (Rezaie, Ferreira and Rahman, 2019). Before cyclone Aila, there was a gradual development of community awareness and preparedness which was further enhanced by a comprehensive disaster management program (Kirsten and Uddin, no date). However, Cyclone Sidr ended up as a deadly disaster despite such developments. The emergency response suffered by ineffective logistic planning and resources. After Cyclone Sidr, the government emphasized the need of rehabilitation of coastal infrastructures and building organizational capacity of the government and NGOs for emergency response (ERD, 2008). The government started a program for rehabilitation of coastal polders but the implementation was yet to start in 2009 (World Bank, 2017). However, there were limited efforts to resolve root causes of exposure to cyclones e.g.

growth of settlements in isolated places highly exposed to cyclone, lack of land-use-planning, poor maintenance of coastal polders, etc.

At the time of Cyclone Aila, there have been improvements in disaster awareness. Actions in response to increased awareness (precaution, evacuation behaviour, emergency measures, etc) were improved, e.g. risk communication and preparedness were improved by providing training to volunteers (Parvin et al., 2019). However, the still existing lack of cyclone shelters was a major reason of non-compliance to evacuation order (Ahsan et al., 2016; Parvin et al., 2019). Improved emergency measures to prevent breaching of coastal embankment (e.g. placing of sandbags, piling of wood-logs) were able to reduce the breaching of embankments (237 km of embankment washed away). The government had improved the emergency capacity of the local governments. The comprehensive disaster management program was re-designed to strengthen emergency capacity (Kirsten and Uddin, no date; Paul and Routray, 2013). Additionally, there was an improvement in government's and NGOs capacity of emergency response. The government handled the emergency situation in a partnership approach with national and local NGOs (Sadik, Nakagawa, R. Rahman, *et al.*, 2018). This GO-NGO partnership in emergency repair of coastal polder and rural roads were appreciated by local people (Sadik et al., 2019). The coordination among international humanitarian organizations was improved. But, there was no significant change in respect to coping capacity. Recovery after Aila even took longer than after Sidr, e.g. recovery of infrastructures was delayed which eventually delayed livelihood recovery. A positive development after Aila was that people were found to be adopting more non-erosive coping strategies e.g. use of savings rather than sell of land and assets (Ferdous, Baqui and Scheyvens, 2015). On the other hand, an increase of dependency on humanitarian aid undermined the local coping capacity (Ferdous, Baqui and Scheyvens, 2015). Still, the overall vulnerability to storm surges at the time of Aila was lower in comparison to the pre-disaster condition of Sidr.

Summary

In both events, major damage were associated with the unavailability and inconvenience of cyclone shelters, poor accessibility, and less trust on cyclone warning (Ahsan *et al.*, 2016; Parvin *et al.*, 2019). Such limitations undermined the expected outcomes of community training, disaster campaigns and other disaster awareness programs of the Government and NGOs.

In the aftermath of Cyclone Sidr, NGOs and the government took initiatives to better allocate equipment and relief supplies to improve emergency response and reconstruction. Pre-disaster allocations and stockpiling at the local level led to a rapid response before, during and after the disaster (UNDP, 2010). The response coordination structure established after Cyclone Sidr contributed to better logistical planning and implementation of the emergency response to Cyclone Aila. As a result, some dike breaches were prevented, e.g. by piling up sandbags and logs. The lower number of dike breaches during Cyclone Aila, compared to Cyclone Sidr, contributed to a significant reduction of impacts.

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ID 21

Paired drought events: event 2006 and event 2015 droughts in the Wielkopolska Province in Poland

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Short description of both events with a focus on impacts

In the area of Poland, the 2006 drought developed quickly during the last decade of June and lasted till the end of July, following the characteristics of a "flash drought". Before the event onset the abundant rainfall in May had a positive effect on the moisture content of the topsoil. In June, agrometeorological conditions varied, while lack of rainfall began to be apparent in the third decade of June. High air temperature, high sunshine and no systematic rainfall, which would improve soil moisture, meant that from mid-July in many regions of the country the condition of agricultural crops deteriorated rapidly. Accelerated ripening of cereals resulted in insufficient grain development. In the second decade of July, the regions experienced very intense, short-duration storm rainfall. In August, strong, recurrent rains occurred in many regions of the country, resulting in longer vegetation, which negatively affected the quality of cereal crops. In Wielkopolska Province, the harvest of basic cereals with cereal mixed was 22% lower than in the previous year, the harvest of potatoes was reduced by 15%, and the harvest of rape and turnip rape was reduced by 5% in comparison to the harvest gross from hectare of sown area. The smallest reduction of 1 % was noted for sugar beets.

The drought event of 2015 was observed since the last decade of May 2015. Initially at the beginning of the growing season moisture of the topsoil met the water needs of the plants. In April exacerbating rainfall deficit begun to cause a soil water stress for crops. In May, cold weather and a lack of rainfall contributed to the slower development of plants. Dryness of the topsoil has occurred in many areas of the country. In June continuation of the unfavorable agrometeorological conditions was observed i.e. rainfall deficit contributed to the exhaustion of soil moisture reserves. In July rainfall totals were still below long-term averages whereas temperatures began to exceed standard values. During the next three months a precipitation deficit continued to deepen along with the rise of temperatures leading to evolution of soil moisture drought. Such conditions lasted practically until the end of the year.

At the beginning of soil moisture drought in May 2015 , the most vulnerable regions to moisture deficiency were the central and north provinces. In subsequent periods, this area expanded and in the first decade of August soil moisture drought was observed for about 2/3 of the country's agricultural area, locally with extreme intensity of soil moisture deficit. In conditions of an extreme deficit of rainfall and very high temperatures occurring in many parts of the country, crop yields were lower than last couples of years. Decreased yields affected the volume of the harvest and the fall in domestic supply of most crop products. The largest decline in production was recorded for root crops and vegetables.

In Wielkopolska Province, the harvest of basic cereals with cereal mixed was 12% lower than in the previous year, harvest of potatoes was reduced by 27%, harvest of sugar beets was lower by 25% and harvest of rape and turnip rape was reduced by 12% in comparison to the harvest gross from hectare of sown area. As the consequences the prices of the crop products per 1 ha of agricultural land increased by 19% in the first-half of the 2006 and by 13% in the second-half of 2015 comparing to previous years 2005 and 2014 respectively.

Descriptions of processes between events with a focus on risk management

In 2006 the Minister of Agriculture and Rural Development recommended that voivodship marshals (governors of administrative polish areas) prepared voivodship agriculture irrigation programs which were completed by 2013. These documents were directed mainly at agricultural users and aimed at indicating the needs for the construction and modernization of water damming devices and irrigation systems to mitigate drought effects. The organisations responsible for the implementation of agricultural irrigation programs were the provincial managements of drainage and water facilities. The implementation resulted in a slow increase of the arable land area equipped with the devices maintaining water in a drained area. Annually, this increase was estimated at the level of 2.56% [KACA 2014].

The area of reclaimed agricultural land in 2006 covered 55 % of the total area of agricultural land. Of the area of arable land 760,4 thousand ha was drained and 11,4 thousand ha was watered. In 2015 arable land covered 54,3% of the total area of agricultural land. 758,2 thousand ha was drained and 10,4 thous and ha was watered. Despite the slight change in drained and watered area, the irrigation method changed substantially, which helped to reduce water withdrawal. The watered area with wet soil method covered 20 569 ha in 2006 and 19 414 ha in 2015 and the spinkler irrigation method was applied to 1 546 ha in 2006 and 2 115 ha in 2015. Water withdrawal for irrigation of agricultural land and forest land was estimated at 16 114 cubic decametres in 2006, made up of 14 351 cubic decametres for wet soil irrigation and 1 739 cubic decametres for sparking irrigation. In 2015, water withdrawal was 16 136 in cubic decametres, made of up 14 824 cubic decametres for wet soil irrigation and 1 276 cubic decametres spinkler irrigation.

In 2005 a new "Small Retention of Water Program for the Wielkopolska Province" was developed that included updated and revised versions of the previous programs established for hydrographic catchments and administrative regions within the Wilekopolska Province.

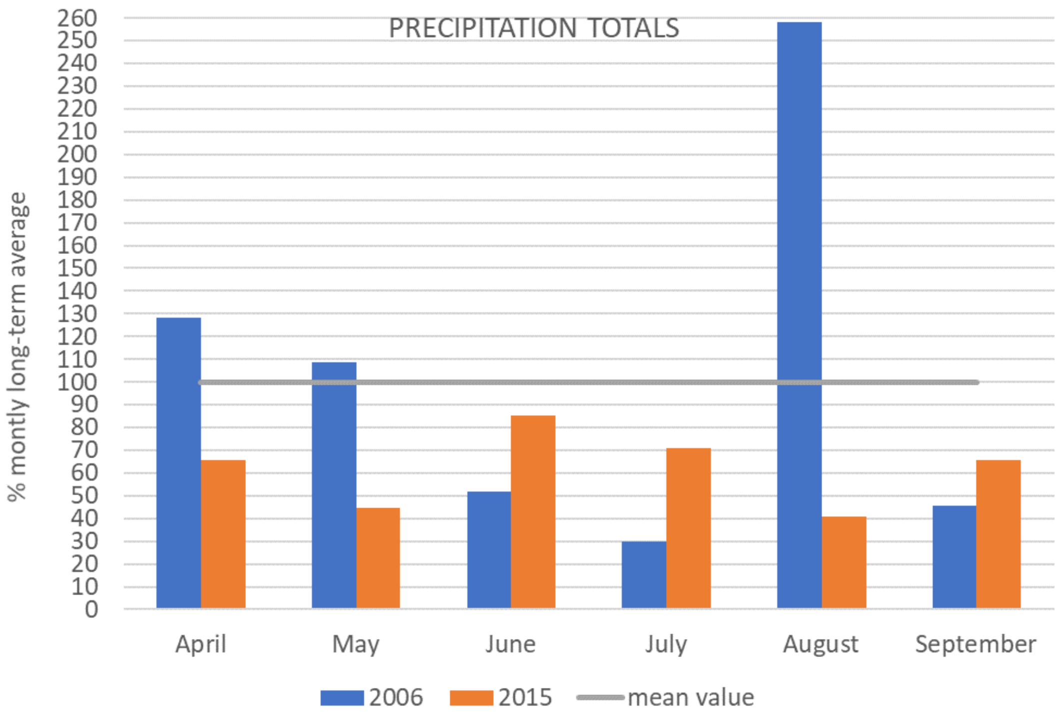
The implementation of the planned small retention facilities by 2015 implied an increase in the amount of water retained. The implementation of the program between 2006-2015 contributed to an increase in the number of small water retention objects from 5859 in 2006 to 6802 in 2015. The total retention capacity of these objects changed from 171 135.6 thousands m^3 in 2006 to 189 880.7 thousands m^3 in 2015.

Event comparison in respect to drought hazard

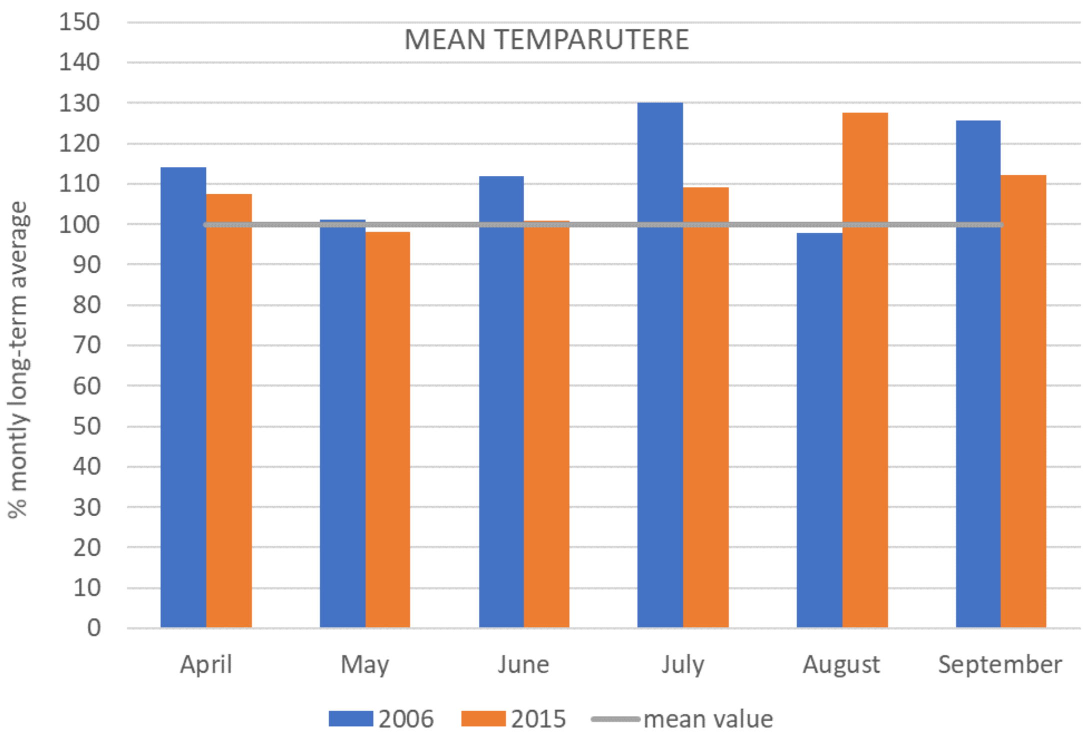
Wielkopolska is influenced by oceanic air masses that affect the mildness of the climate. The area is situated in the Silesian Greater Poland agro-climatic region where the average annual temperature is about 8.8°C. Precipitation ranges from 500 to 550 mm.

In 2006, precipitation at the beginning of the vegetation period April-May was moderately higher than long term-average, reaching monthly totals of 50 mm in April and 66 mm in Maythat was close to 20 % higher than mean values (Fig. 1a) Temperature was slightly higher than normal value, with mean monthly values around 9°C in April and 13.5°C in May. Between the beginning of June and the last decade of July the total precipitation in the region was much lower than the long-term average. In June total precipitation was lower by 50% compare to average and the maximum difference from the norm was observed in July, with precipitation totals reaching the level of 18% of the long-term mean (Fig. 1a). This was accompanied with extremely high temperatures – close to 2°C higher than monthly mean in June (110% of long-term mean) and 5°C higher in July (130% of long term mean) – Fig.1b. Drought conditions ended drastically in August when intensive rainfalls resulted in high exceedance of monthly precipitation totals, which were locally more than 200 % higher than the monthly mean. In 2006, within the period of agrotechnical operation from April till September, the mean temperature was 1.3°C higher than the long term mean value and the precipitation deficit was 6% lower on average.

In 2015, the beginning of the vegetation period until the end of June was characterized with temperatures close to long-term mean (Fig.1b), whereas from the beginning of April precipitation deficits in the majority of the Wielkopolska Province started to be observed, precipitation deficit was lasting throughout the whole agrotechnical period from April till September with the largest deviations from long-term mean in May and August (around 40% of long term mean) – see Fig. 1a. The monthly mean temperature in August 2015 was higher by 4,4°C than the long term average. In 2015, within the period of agrotechnical operation from April until September, the mean temperature was 0,9°C higher than long term mean value and the precipitation deficit was 43% on average.



a)



b)

Figure 1 Deviation from the mean values of precipitation (a) and temperature (b) in the respective months of growing season for 2006 and 2015 drought (source: own study)

The drought indices Effective Drought Index (EDI) [Byun and 1999] and Standardized Precipitation-Evapotranspiration Index (SPEI) [Vicente-Serrano, 2010] were applied to help identify onset, duration and intensity of respective drought events. The applied drought indices were estimated based on the measurements from monitoring network operated by Institute of Meteorology and Water Management National Research Institute. Within the area of Wielkopolska Province precipitation was measured on 18 stations, temperature on 9 stations, wind speed on 5 stations and relative humidity on 6 stations. The reference period required for the calculation drought indices was set on 1971 – 2005.

From the EDI plot drought conditions in 2006 for the majority of the area began in mid June. The lowest EDI values were estimated for the end of July, varying around value -1.3 with extreme EDI value close to -2. According to the EDI index, moisture conditions were back to normal around 5th August (Fig. 2). Drought conditions lasted for 1,5 monts.

The spatial distribution of the SPEI index developed for 2006 proves that soil moisture drought conditions in July 2006 corresponded to severe drought (SPEI between -2,0 and -2.5) for the vast majority of the region (Fig. 3).

In 2015, based on EDI values dry conditions had begun in the majority of Wielkopolska Province by mid May, and except for the last decade of July they lasted until the end of the year (Fig. 4). Within the period April-September the driest conditions were observed at the beginning of June with the lowest EDI value below -2 in the mid of the month and then in August gradually decreasing from the beginning of themonth, and then once again EDI values falling below -2locally. Precipitation recorded in November was not sufficient to return to normal moisture conditions by the end of the year according to EDI information.

According to the SPEI index developed for 2015, the extreme of soil moisture drought was observed in August 2015 when the entire Province area was in a state of to severe or extreme drought with the majority of SPEI indices falling below -2.5 (Fig. 5).

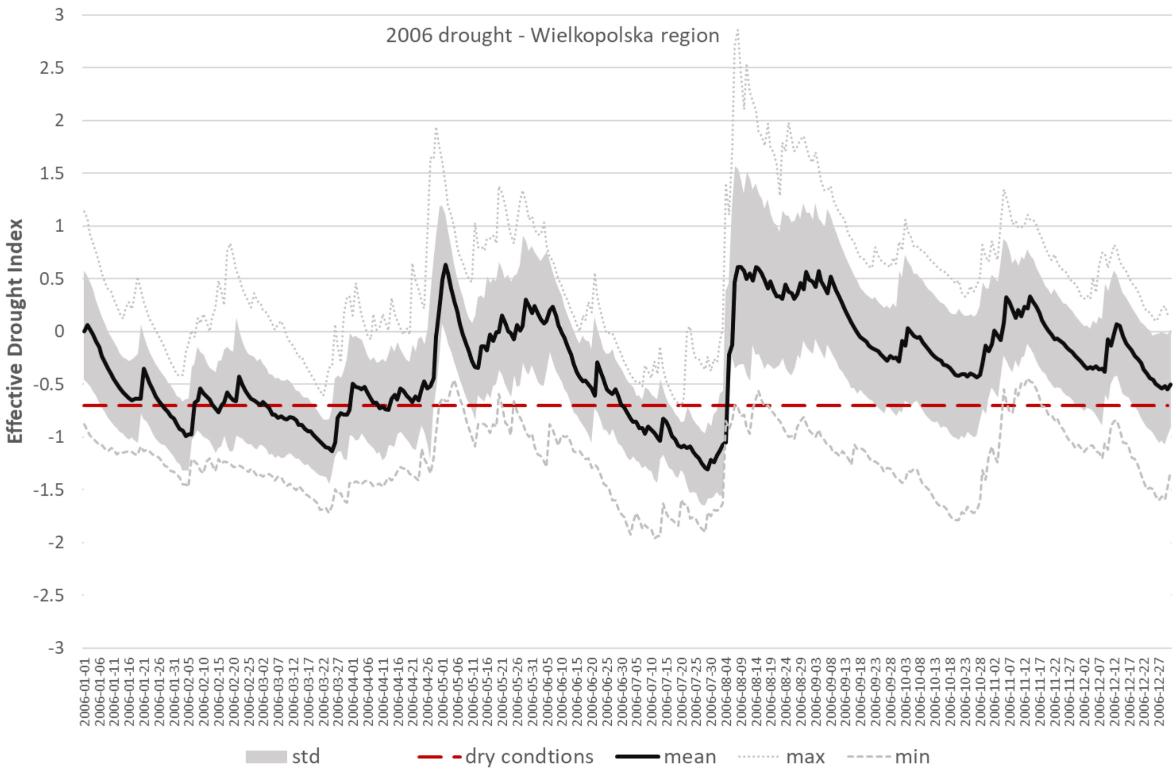


Figure 2 EDI plot for 2006 based on information from 18 precipitation stations located within the Wielkopolska Province (source: own study).

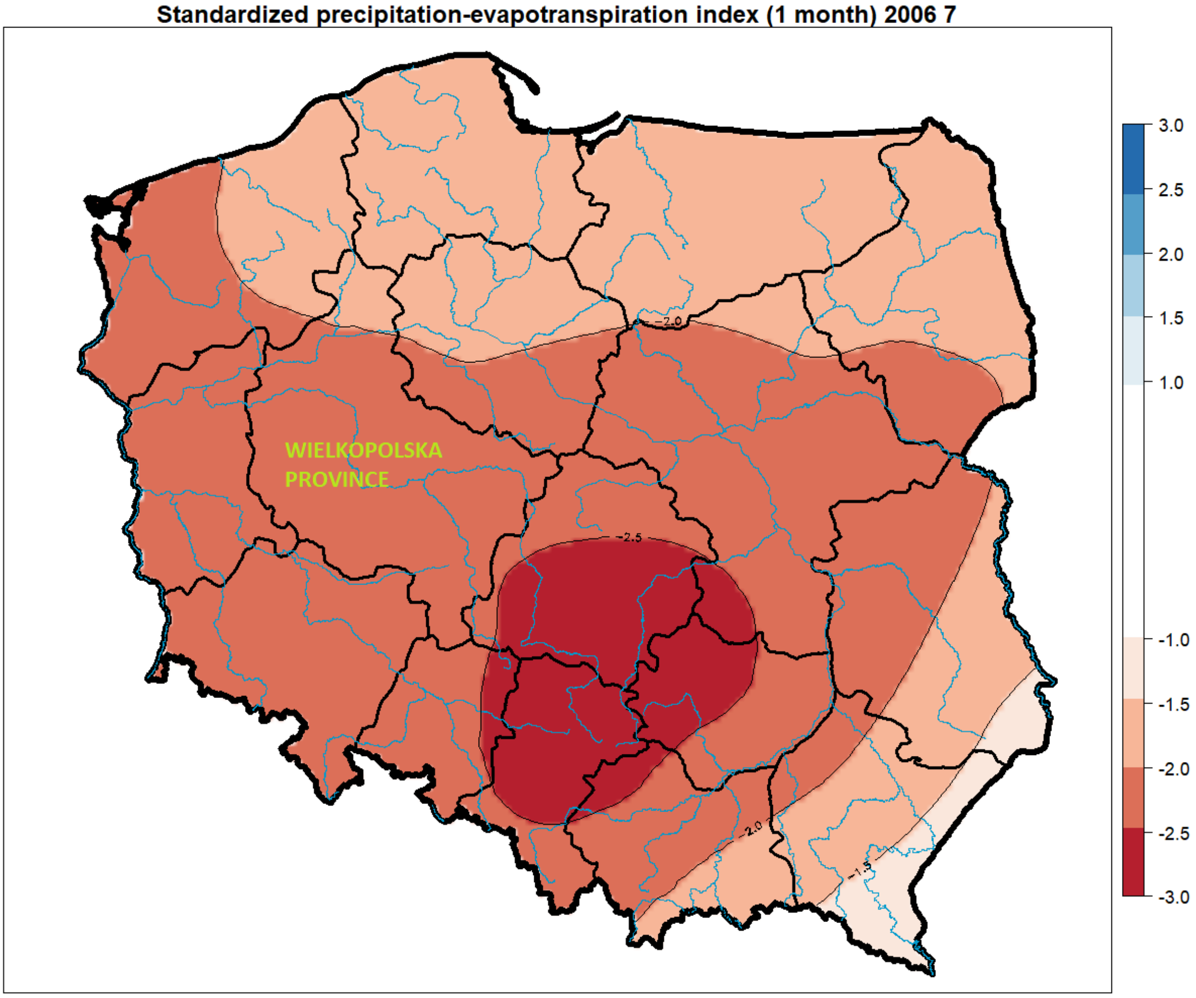


Figure 3 Spatial distribution of 1-month SPEI values estimated on the end of July 2006 (source: own study)

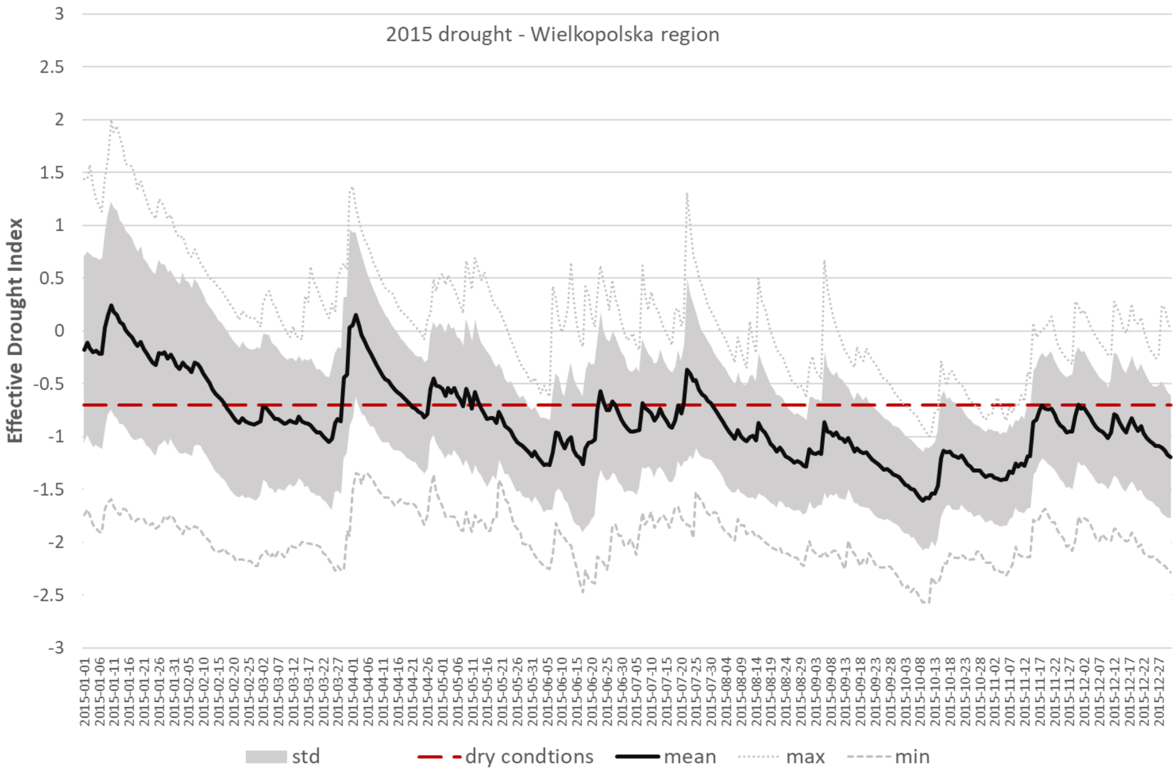


Figure 4 EDI plot for 2015 based on information from 18 precipitation stations located within the Wielkopolska Province (source: own study).

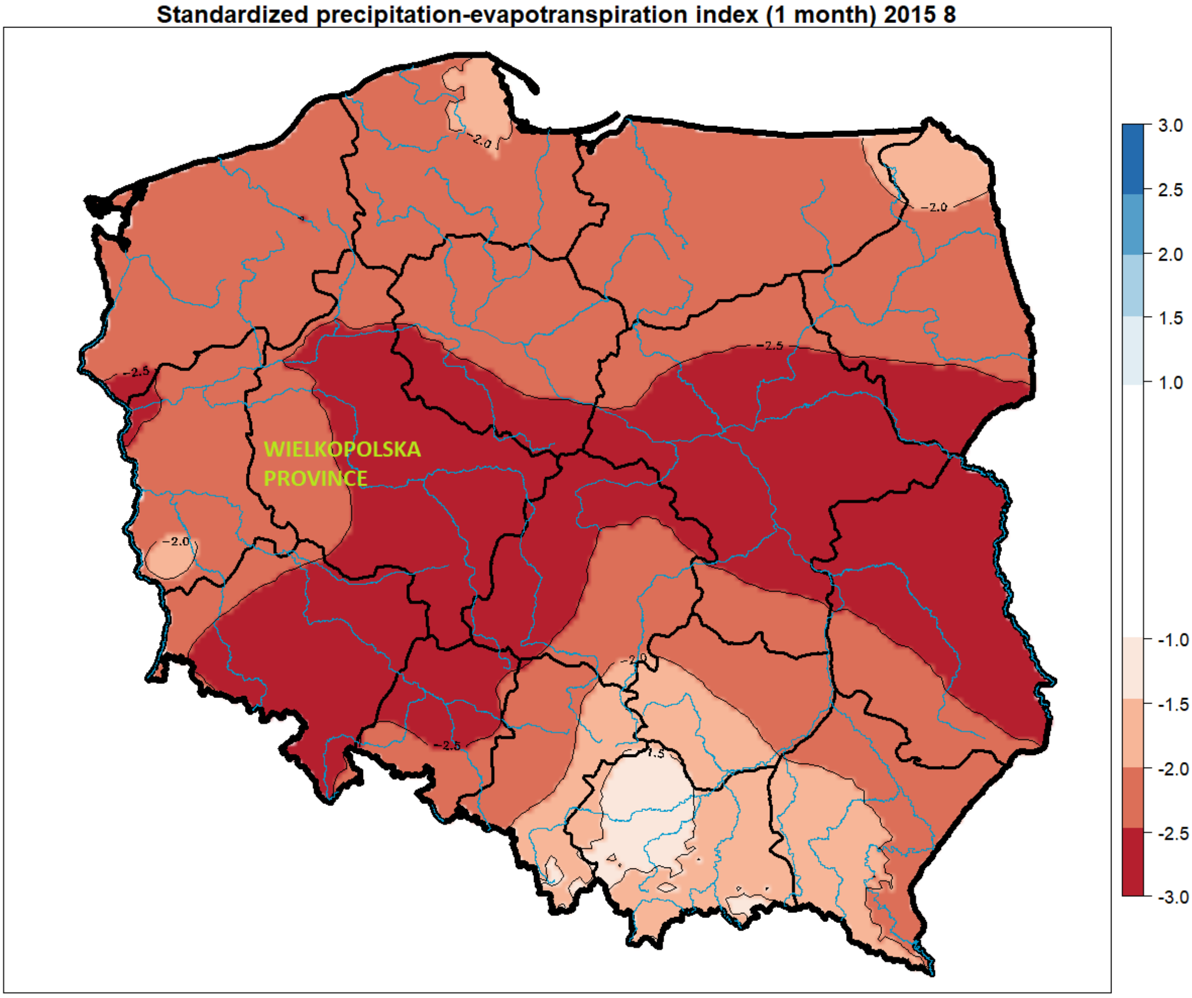


Figure 5 Spatial distribution of 1-month SPEI values estimated on the end of August 2015 (source: own study).

Event comparison in respect to exposure

Wielkopolska Province is located in the west-central part of Poland. With an area of close to 30,000 square kilometres and population of close to 3.5 million, it is one of the largest Polish provinces. The capital city of the province is Poznań, with more than 565,000 inhabitants.

Most of the Wielkopolska region lies within the basin of the middle Warta River, which is the largest right tributary of the Odra River. The Warta river drains through the agricultural area of the Polish plain. Agriculturally fertile soils account for around 60% of the province's area. The growing season is one of the longest in Poland. On the province's southern plains this season lasts for around 228 days, while towards the north of the region it gradually declines to 216 days.

Wielkopolska Province remains the largest producer in agriculture in Poland. In general the voivodship's share in the national production is around 15% of cereal production, 14% of potato, 21 % of sugar beet. The rapeseed and turnip rape harvest is at the level of 11 % which is the second largest share in domestic production. In 2006 share in the national production of Wielkopolska Province was at the following levels: basic cereals with cereal mixed 13,5%, potatos 9,1%, suger beets19,2% rape and agrimony 13,4%. In 2015 the share of potatoes increased up to 10,8%, of sugar beets up to 22,2% whereas the share of rape and agrimony was lower (12,1%)

Agricultural areas dominate in the total area of the province. The area of agricultural land is around 1800 thousands ha and individual farms constitute close to 86% of the total utilized agricultural area. The extensive development of agriculture in this area has contributed to the intensive regulation of watercourses and wetland drainage. The result of regulatory work was the conversion of natural river ecosystems to agricultural land and the reduction of diversity of the natural environment, as well as the need to maintain hydrotechnical constructions on rivers (Mioduszewski, 2017). In consequence, a decrease of natural soil retention and reduction of groundwater supply is observed which clearly increases the risk of soil drought leading to a drying of the area.

The Wielkopolska Province is considered to be the most scarce in water in Poland. The great exposure to the effects of drought is recognized for 43 communes located in the central, eastern and southwestern part of region. An unfavourable water balance results from low rainfall and unit runoff below the national average, as well as limited possibility of natural and artificial water retention. This negative situation is also aggravated by the expanded sealed surface, mining (in particular open-cast mining of minerals) and insufficient afforestation. The sector of agriculture remains the most exposed to drought. In 2006 the number of people employed in agriculture sector in the Wielkopolska Province was estimated on more than 205 thousands people in 2015 more than 209 thousands.

Although the total sowing area in Wielkopolska Province was similar in 2006 and 2015, the sowing structure was different. In 2015 the sowing area of cereals with cereal mixed was smaller by 175 500 ha (16%), potatoes by 23 000 ha (42%), sugar beets by 50 400 ha (10.5%) while sowing area of rape and turnip rape has increased by 83 700 ha (31%).

Event comparison in respect to vulnerability

On the country level, between the 2006 and 2015 drought events, an amendment of the Water Law Act from 2001 took place in 2012. As part of the amendment, the issue of protection against drought was separately identified and it was pointed out that protection against drought was carried out in accordance with the drought mitigation plans in river basin and drought mitigation plan in water regions.

Drought mitigation plans include: 1) analysis of the possibilities of increasing available water resources; 2) proposals for the construction, modernization or reconstruction of water facilities; 3) proposals for necessary changes in the use of water resources and changes in natural and artificial retention. Drought mitigation plans also contain a catalogue of measures to reduce the effects of drought.

Nevertheless, this amendment did not have significant influence on drought coping capacity as, for the Warta water region, the drought mitigation plan was developed and approved in 2017.

At the level of the province, documents on planning drought mitigation measures can be divided into two groups:

- documents related to spatial development and voivodship development (development strategies and their updates, environmental protection programs, spatial development plans)

- investment programs covering two types of activities: agricultural irrigation programs and small retention programs.

Locally drought protection is organized at the commune level. So far, only a quarter of the municipalities located in the Wielkopolska Province have a document related to drought effect mitigation. The vast majority of these documents concerned operational activities - directly or indirectly related to the crisis management at the time of drought.

Summary

Wielkopolska Province remains one of the most drought vulnerable region in Poland due to unfavorable climatic conditions with climatic water balance reaching -150 mm (Kozyra, Górski, 2004) whereas providing up to 1/5 of total crop national production in the same time.

Developed between 2006 and 2015 drought mitigation strategies have resulted in slight increase in drought resistance i.e. number and capacity of small water retention objects. However, the usable capacity of water reservoirs for melioration or watered area of arable land remained at the same level. Slight changes were introduced to irrigation infrastructure and management with progressing watering with sprinkling machines and reducing water consumption in the same time.

Both drought events 2006 and 2015 resulted in more than 20% reduction of crop production. In 2006 the most severe impacts were observed in the first half of the year resulting in 22% reduction of cereals production and 19% increment of crop prices. Consequences of drought event in 2015 were mostly observed during the second half of the year with 27% reduction of potatoes production and 25% reduction of sugar beets production. The crop production prices increased by 13% compering to previous year.

It can be concluded that the difference in observed drought impacts were mostly associated with the drought hazard characteristics. Other drought risk elements including exposure to drought and vulnerability had marginal effect on the observed drought losses. Therefore, it is crucial to proceed with the development and implementation of drought mitigation plans in the very near future.

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ID 22

Paired drought events: Hydrological drought 2003-06 and 2010-12 in North East Thames Region in the United Kingdom

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Short description of both events with a focus on impacts

General region focusing on – North East Thames region

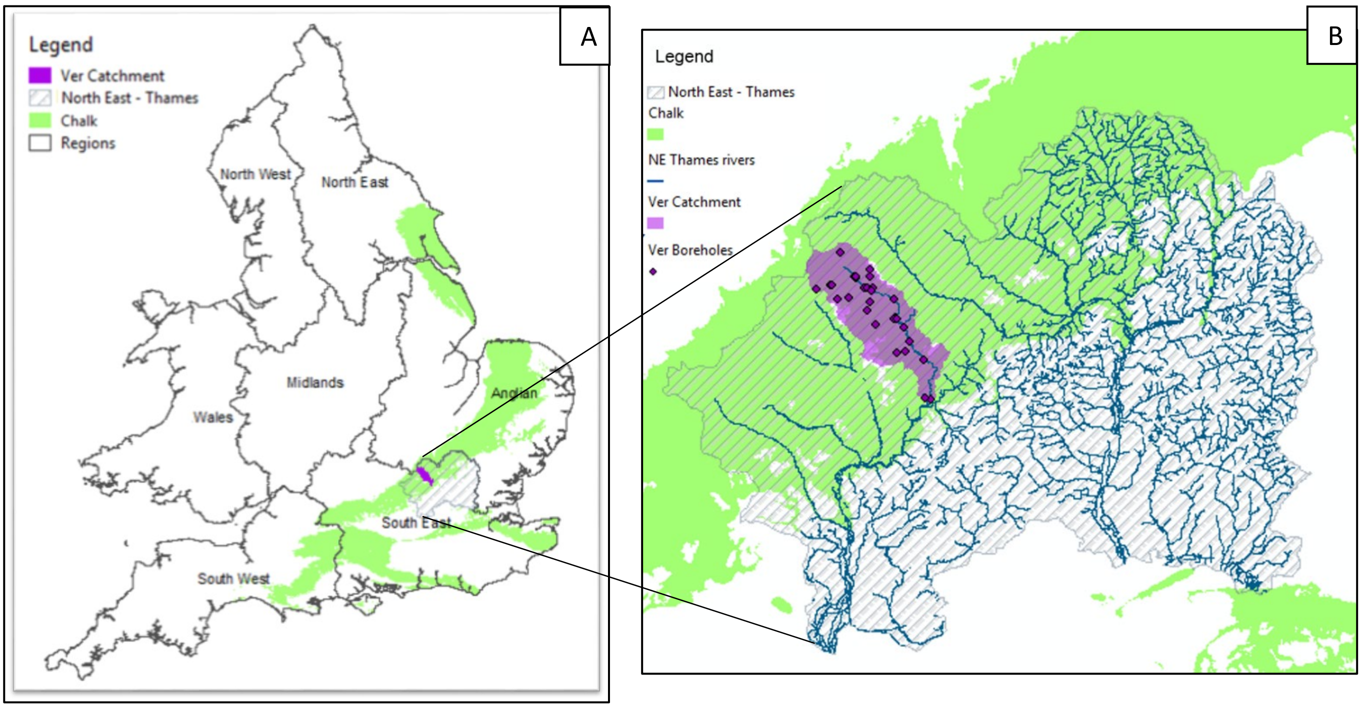

Figure 1. A: North East Thames region in England. 1B: The Ver catchment with main rivers and boreholes used to monitor drought hazard.

Two hydrological drought events in North East Thames region (Figure 1A) are paired that affected a large area in the South East of England**.** The two hydrological droughts affected public and private water users, as water use restrictions were in place. Direct economic impacts of both events were due to reduced agricultural production, road and rail heat damage and fish rescues. Direct environmental impacts were algae blooms, fish deaths, reduced breeding areas for wildlife and loss of habitat from stream network shrinkage.

The 2003-06 hydrological drought impacted 13 million people directly, as water use restrictions were in place in Southern England (Marsh. 2007). Public water supply companies activated drought plans to sustain the water supply for drinking water and essential water use (Barker, 2005). The agricultural sector was bound to restrictions in water use due to a long-term shortage of reservoir storage (Marsh. 2007). The agricultural production of pea and beans was badly impacted by the drought. Positive agricultural impact was due to an increase in the price of wheat and potatoes, as a consequence of drought impacts in Europe (Area Drought Team, 2006c). Other sectors that were impacted by the drought were power stations and navigation (Area Drought Team, 2006a; Area Drought Team, 2007). Tourism benefitted from the warm weather (Durant, 2015). Reported economic impacts are additional costs for road maintenance (£3.6m in Oxfordshire: Durant, 2015). Numbers for economic impacts of the drought on agricultural production are not reported. Reported environmental impacts were mainly fish rescues and reduced fishing in lakes (Hemel Hempstead and Colne; Area Drought Team, 2006a; 2006c; Douse, 2006). Additionally, bird breeding areas were reduced (Durant, 2015) and fish and ducks were migrating due to drying up head waters, reduced oxygen levels, and algae bloom that sometimes resulted in more fish deaths (Area Drought Team, 2006c; Marsh, et al. 2007; Durant, 2015).

In the 2010-12 hydrological drought, 20 million people experienced restriction for non-essential water use (Marsh et al., 2013). Economic impacts of the drought were mainly felt in the agricultural sector that lost 165m in turnover, of which half in irrigated potatoes (Vived Economics, 2013). Farmers struggled to fill their reservoirs (Environment Agency, 2012). In 2012, farmers planted 80% of their lands expecting lower than average yields (BBC News, 2012a). Similar to the 2003-06 drought, the price of some crops increased (St Albans review, 2011). Other than the agricultural sector, landscaping services lost £45m and the golf sector lost £25m. Public water supply sector lost £0.48m in turnover. Impacts on tourism are not reported due to lack of evidence (Vived Economics, 2013). Navigation was negatively affected and due to ground shrinkage canals showed increasing leakage (Marsh, et al. 2013). Unusual fish rescues were required in canals during autumn, winter and spring of 2011-12 (BBC News, 2012b) and wildlife organisations reported reduced breeding areas with possible impacts on the whole breeding season (The Guardian, 2012b).

Descriptions of processes between events with a focus on risk management

Key developments are identified in the timing of drought risk communication and the implementation of water use restrictions (drought permits). During the first drought event, most drought risk communication and drought permits were initiated after drought trigger levels were passed, which implies water availability had already reduced to substantially below-normal. Depleted reservoirs prompted local water transfers (Marsh. 2007). At that moment, awareness campaigns were set up first regionally and then nationally (Walker, 2008; Barker, 2005). Drinking water companies started to apply for drought permits before implementing them (Walker, 2008; Marsh, et al. 2007). During the second event, prolonged dry weather prompted enhanced monitoring and awareness campaigns months before the water availability reached trigger levels and early warnings were given to large water users in the agricultural sector (Environment Agency, 2011a; 2011b; 2011c; 2012a; 2012b; Area Drought team, 2012; North East Thames Region Team, 2012). The implementation of drought permits started earlier in the second drought event and water conservation measures were in place when drought trigger levels were passed (Vivid Economics, 2013; Environment Agency, 2012a).

Risk management changed also in terms of regional organisation. In 2003-06, water use restrictions were imposed at different times in different regions by the national water regulator

(Environment Agency) and public water supply companies (Three Valleys Water, 2006; Holmes, 2006; Health and Public services committee, 2006). The implementation of water use restrictions was incoherent resulting in public criticism and possibly less effective drought management (Health and public services committee, 2006). Risk management strategies were changed for the second drought, in which an Emergency Drought summit was held to coordinate water use restrictions (The Guardian, 2012a). Agricultural water use restrictions were announced early, abstractor groups were set up to manage abstraction across the region and advice was offered on how to reduce water demand (Environment Agency, 2012b). Private water use was restricted regionally, as 12 drinking water companies imposed and removed water use restrictions at (nearly) the same time (Vivid Economics, 2013).

An external factor to the early drought warnings and drought permits in the second drought event might be related to the Olympics that were hosted by the UK in 2012. Water services were under strain in 2012 due to the prolonged drought, and water companies were worried about the potential impact of increased water use during the Olympics on the drought and potential disruption to the games due to drought-related water supply issues (The Guardian, 2012a; Area Drought team, 2012). Significant rainfall occurred just before the Olympics, which effectively brought an end to the drought

Event comparison in respect to drought hazard

Both drought events were driven by a shortage in winter recharge in North East Thames basin and more broadly across the chalk in South East England. The difference between the two events is that in the 2003-06 drought event a heatwave occurred in 2006 that aggravated the deficit in groundwater. The average drought duration in the region is 3.4 years for the 2003-06 drought compared to 2.1 years in 2010-12. This was calculated for this study using the Standardised Groundwater Index (SGI) as developed by Bloomfield & Marchant (2013) of the available groundwater monitoring wells in the catchment of the River Ver (Figure 1B) and using a threshold of less than zero to define drought (SGI<0).
The maximum intensity in SGI was greater for the second drought, on average -1.27 compared to -1.24. The high intensity for the shorter drought in 2010-12 could be due to the delayed or even absent groundwater recharge over the whole drought period of 2010-12 (Marsh, et al. 2013).

Event comparison in respect to exposure

The 2003-06 drought event was particularly intense in the Chalk basins in South East England and affected most of southern England. The 2010-12 drought extended across southern England, impacting the South East most severely, as well as affecting regions in the Midlands and parts of Yorkshire (Figure 1A**,** Durant, 2015; BBC News, 2012c). 13 million people were exposed to water use restrictions across Southern England during the 2003-06 drought (Marsh, et al. 2007). Intermittent chalk rivers such as the Ver catchment were particularly vulnerable due to low flows, which then resulted in some fish rescues (Environment Agency, 2005). The spatial extent of the second drought event was larger (Central, Southern, and Eastern UK) resulting in a larger exposure of 20 million people across England (BBC News, 2012c; Kendon, et al. 2013). Urban areas were considered hotspots, i.e. London (The Guardian, 2012c).

Event comparison in respect to vulnerability

It seems that the vulnerability reduced from the first to second drought event. This is because of earlier preparations in the second drought event. For example, public awareness campaigns started only when the water availability was below some drought trigger levels in the 2003-06 drought (Barker, 2005; Walker, 2008). Local groups had already flagged the presence of low flows and added pressure on management level (Environment Agency, 2005). During the drought, drought teams were established and different management plans and scenarios were made to estimate reservoir and groundwater availability. In the last year of the drought, after the implementation of water use restrictions, more public awareness campaigns were initiated including radio and TV interviews (Area Drought Team, 2006a; Health and Public Services committee, 2006). The restrictions caused public criticism due to delayed maintenance of the water supply system resulting in slow repairs of leaking pipes (Holmes, 2006; Lewis, 2006; St. Alban's Review, 2006). This criticism resulted in a reluctance to cooperate with drinking water companies (Durant, et al. 2015).

In the 2010-12 drought, a seasonal forecast was used to estimate the potentially affected area (Environment Agency 2011a). Public awareness campaigns were started earlier (before the water availability was at trigger level) and water use restrictions were communicated widely via the national television *before implementation* (Area Drought team, 2012). The Environment Agency has been more pro-active in advising farmers about drought, water use and abstraction licences (Environment Agency, 2011a; North East Thames Region Team, 2012; Environment Agency, 2012a; Area Drought team, 2012). Public participation was started to report leakage of water systems and meetings with local groups were setup (St. Albans Review, 2012; Area Drought team, 2012). Despite the increased effort on public management, there was still criticism for failing to maintain leaky pipes (The Guardian, 2012b).

The coping capacity seems to increase from the first drought event to the second. Drinking water companies reported that the imposed water use restrictions in 2006 would be enough to save water for 7% of the households during critical periods. These are, however, estimates of the planned effectivity of the water use restrictions (Health and public services committee, 2006). In the second drought event, households and the agricultural sector saved approximately 170,000Ml water. A large component of the coping capacity was due to the reduction of irrigation (potatoes) that introduced major losses to the agricultural sector. Water saving strategies on other crops, landscaping services, and golf were short-lived due to the late timing of these actions (Vivid Economics, 2013).

Summary

There are hints of an Adaptation effect, because drinking water companies and the Environment Agency changed their drought risk management since the first drought event. Risk management started earlier in the second drought event and there was more engagement with industry and media campaigns to raise awareness with the public after important lessons were learnt. Weather forecasts were used earlier and early warning systems warned farmers and drinking water companies for potential water use restrictions. These restrictions were implemented in a more consistent manner in the second drought event resulting in a larger coping capacity. However, this coping capacity was largely due to a reduction in agricultural water use that came with large economic impacts. Water use restrictions were in place for other sectors, although the impact was limited due to the late timing.

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ID 23

Paired drought events: 2003-2004 and 2005-2006 droughts in the UK

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Despite the United Kingdom (UK) being known for its humid and temperate climate, meteorological, soil moisture and hydrological droughts are a common occurrence. From 2000-2010, the UK experienced a period of significant climatic and hydrological variability with some of the wettest periods (e.g. the 2007 floods) and driest periods (e.g. the 2003-2004 and 2005-2006 droughts) on record. This case study describes the 2003-2004 and 2005-2006 droughts in detail focusing on a comparison between the impacts, risk management, vulnerability, hazard and exposure between the two events.

Short description of both events with a focus on impacts

The 2003-2004 drought was a UK-wide event with record summer temperatures in 2003. There were wide-ranging meteorological drought impacts in 2003 due to the associated heatwave which led to an estimated 2000 deaths (BBC News, 2003) and impacts on transport networks, ecology, manufacturing and agriculture. In contrast, the 2005-2006 drought had a strong regional focus with low rainfall totals over a long time period. For this drought, the impacts are more associated with the hydrological drought and impacts from water use and abstraction restrictions.

It is important to note that while these events are described as two separate events, due to the memory of groundwater systems in the South-East of England, they are closely linked with respect to groundwater resources.

Meteorological Drought. The impacts from the associated heat wave during the 2003-2004 drought were substantial and particularly affected health (2000 deaths, estimated £41 million cost to the health sector), transport (through melting tarmac and buckling train lines) and manufacturing (BBC News, 2003; Hunt, 2007). The 2005-2006 drought also had an associated heatwave in 2006 which was less severe (680 deaths; Public Health England, 2019) and less reported impacts on health, transport and manufacturing. The impact to livestock from the heatwave was relatively minor and consistent between the two events.

Soil Moisture Drought. Spray irrigation restrictions were imposed during both droughts with likely impact on some farmers. Due to the high temperatures in 2003, there were also problems associated with leakage due to soil shrinkage (Marsh, 2004).

Hydrological Drought. In 2003-2004, there was a limited impact on water resources due to very healthy antecedent surface and groundwater resources. However, there were some ecological impacts from the hydrological drought related to stress on fish and fauna and a general deterioration of water quality due to the low flows and high temperatures (Marsh, 2004). In contrast, 2005-2006 had much broader impacts from the hydrological drought with hosepipe bans affecting over 15 million people (EA, 2017) and water use restrictions for over 13 million in the south of the UK (Marsh, 2007). There were also environmental impacts associated with the very low flows in rivers.

Descriptions of processes between events with a focus on risk management

The 2003-2004 drought event showed relatively even intensity of drought across the UK, though with some limited extreme local impacts, e.g. restrictions on spray irrigation. In those problem areas, the activation of stand-by sources, the granting of drought permits (EA 2004) to allow, for instance, additional abstraction to supplement dwindling reservoir stocks, and widespread publicity campaigns to moderate water demand also played a significant role (Marsh, 2004). However, for the 2005-2006 drought event, a number of drought mitigation measures was used more widely including publicity campaigns to moderate demand, hosepipe bans to more than 15million people, local water transfers, restrictions in spray irrigation, reductions in compensation flows and temporary switching of depleted reservoirs to non-consumptive mode (Marsh, 2007). As a result of the Water Act implemented during 2003, there was stronger legislative framework in place for the drought event in 2005-2006 compared to 2003-2004.

Event comparison in respect to drought hazard

Meteorological Drought. Standardised Precipitation Index (SPI) was calculated from the CEH Gridded Estimates of Areal Rainfall (GEAR) dataset which provides daily rainfall on a 1km^2 grid over the United Kingdom (Keller et al., 2015; Tanguy et al., 2016). SPI was calculated for a 12-month accumulation period using a gamma distribution.

The 2003-2004 drought was UK-wide with a relatively even intensity. The Feb-Oct 2003 was the driest since 1921 and this can be seen with a steep decline in SPI for all regions. SPI reaches values of less than -1 for all regions during the 2003-2004 drought. However, this is relatively short-lived with most regions only experiencing SPI less than zero for 2-3 months with the exception of the North West which has a SPI less than -1 for 11 months. In contrast there are large regional differences in meteorological drought during the 2005-2006 drought. The lowest SPI's are in the south and south-east of the UK with a long period where SPI is below zero (24 consecutive months for the South East). In contrast, the west and north of the UK were much wetter with SPI's above zero.

Soil Moisture Drought. No data available

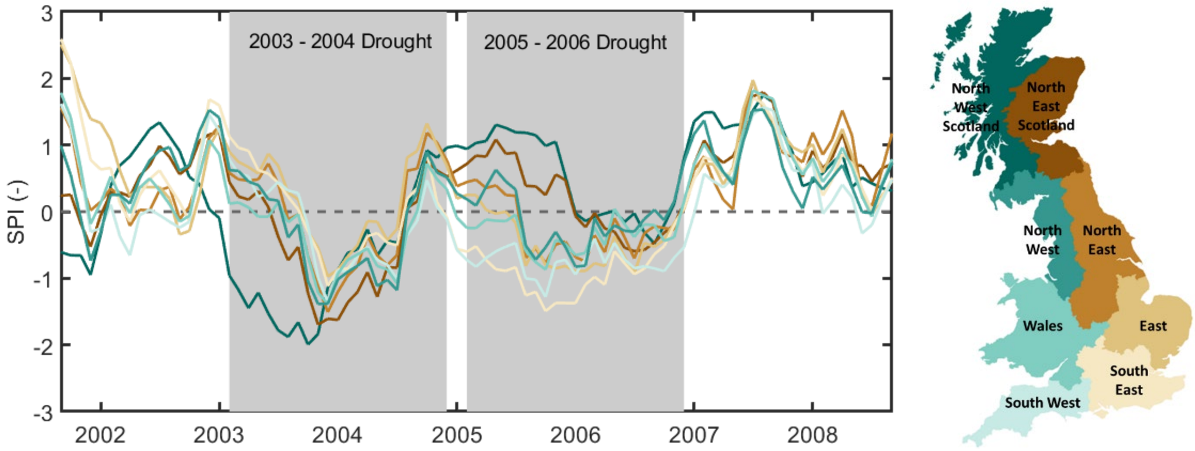

Figure 1 | 12 month Standardised Precipitation Index calculated using a gamma distribution, averaged over eight different regions across Great Britain from September 2001 – September 2009. The areas shaded in grey highlight the two drought events.

Hydrological Drought. June-October flow averages were calculated from daily flow timeseries obtained from the CAMELS-GB dataset (Coxon et al, 2020a,b) for every year from 1970 – 2015 for 671 catchments across Great Britain. A long-term average for all years was calculated and then the percentage deviation of mean June – October flows in 2003, 2004, 2005 and 2006 from the long-term average was calculated to show the impact of the drought on the flow regimes for the different drought events (Figure 2).

The 2003-2004 drought event, as reflected in the SPI data, was a drought event that affected river flows across the UK. On average river flows were 45% below the long-term average for these months in 2003 and 93% of the gauges analysed were lower than the long-term average. In 2004, it is evident that many of the gauges have returned to above normal flows except for gauges in the south-east and south, which are still less than the long-term average. This trend of low flows in the south and south-east persists in 2005 and 2006 predominantly due to memory in groundwater systems. On average, river flows from June-October were 22% (2005) and 21% (2006) lower than the long term average but 130 gauges predominantly concentrated in the South-East recorded lower average flows during these months compared

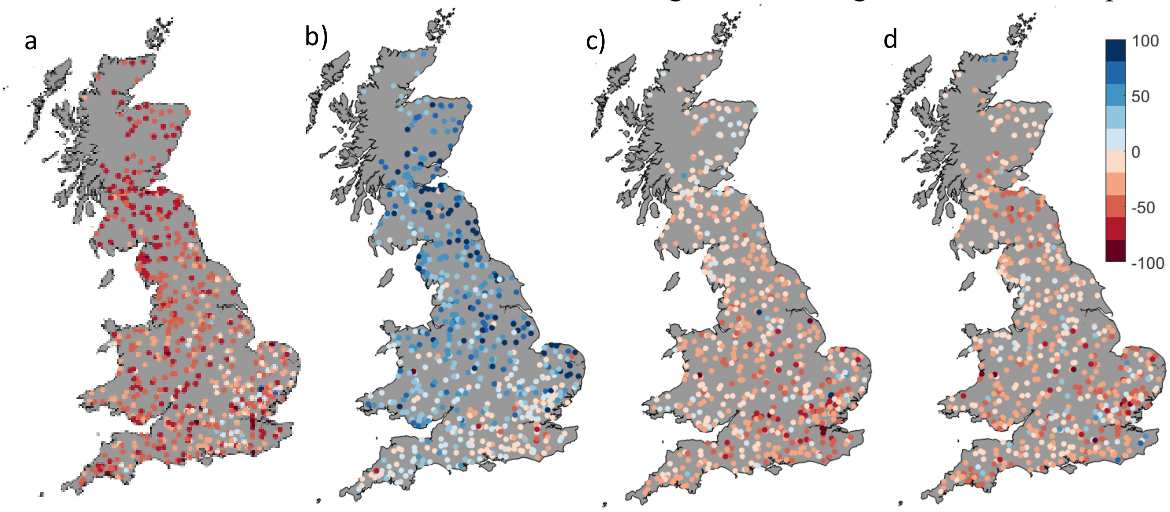

Figure 2 | Percentage deviation of mean June-October river flows the long-term average in a) 2003, b) 2004, c) 2005, d) 2006 to 2003. The trend of low flows is more consistent across the country in 2006 as reflected in the SPI.

Event comparison in respect to exposure

Meteorological Drought. The meteorological drought and associated heatwave of Summer 2003 had a national impact affecting ~60million people. In contrast, the meteorological drought and associated heatwave of Summer 2006 had a more regional impact with hotspots in the South and East of the UK.

Soil Moisture Drought. Many farmers were exposed to soil moisture drought during both events. However, farmers in eastern and southern England were particularly affected during the 2005-2006 drought, with an exposure hotspot in East Anglia which was placed under a number of irrigation restrictions. Farmers throughout the UK were affected during the 2003-2004 drought with widely reported drops in crop production and yield for many types of crops. Winter oilseed rape was particularly badly affected during the 2003-2004 drought.

Hydrological Drought. Limited exposure to hydrological drought during the 2003-2004 drought event. However, high exposure in southern and eastern areas for water users during the 2005-2006 drought event with over 15 million people subject to a hosepipe ban. Navigation was also affected on the River Thames during the 2005-2006 drought event.

Event comparison in respect to vulnerability

The management options implemented during the Water Act (2003) seemed to cope reasonably well for both drought events (though the 2005-2006 drought event triggered many more of these options). In particular, there was a stronger legislative framework in place during 2005-2006 (Marsh et al., 2014), while many companies lacked baseline environmental studies at the beginning of the drought in 2003-2004 (EA, 2004). In both cases, subsequent wet autumn/winter periods resulted in a relatively quick recovery.

However, the protracted drought during 2005-2006 highlighted the vulnerability of England and Wales to successive dry winters – this triggered the need for improved understanding of when clusters of dry winters occur (medium-term climate variability) (Marsh, 2007).

Summary

The UK 2003-2004 and 2005-2006 drought events were interestingly different because of their spatial differences in intensity, duration and pre-drought conditions. The closeness of these two drought sequences and then the subsequent extreme flooding in England in 2007 led the government to publish a water strategy report that outlined the UK's future ambitions for maintaining clean water for people, businesses and nature for England (Defra, 2008). Neither of these drought events caused extreme impacts, especially when compared to the UK drought of 1976, or indeed a number of more significant drought and heatwaves that have occurred throughout Europe. However, they were deemed significant enough to cause concern as to how climate change and increasing population densities, especially in the South East, might make the UK more vulnerable to such 1-2 year drought periods in the future.

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ID 24

Paired drought events: 1976 (event-year1) and 2003 (event-year2) droughts in the Meuse and Rhine catchment in Europe.

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Short description of both events with a focus on impacts

The 1976 and 2003 droughts resulted in strong declines in streamflow in the Meuse and Rhine catchments. At station Eijsden (Dutch-Belgium border; Meuse) the number of days with extreme low flow (i.e. streamflow lower than the long-term 5-percentile streamflow) was 151 days in 1976, and 73 days in 2003. Both droughts resulted in deterioration of water quality with respect to water temperature, eutrophication (with a doubling in ammonia and ortho-phosphate concentrations), major elements (with increased concentration up to 50%, e.g. chloride, fluoride, sulphate), some heavy metal and metalloids (e.g. arsenic).

Descriptions of processes between events with a focus on risk management

The overall water quality status of the Meuse and Rhine rivers has improved between 1976 and 2003 due to environmental policy measures, construction of waste water treatment plants and technological developments (Voltz et al., 2002). Several sectors are depending on the availability and quality (or temperature) of water resources, e.g. for drinking water production, irrigation, power generation, manufacturing, recreation and ecosystem functioning. Risks for sector water use are in particular large during droughts, in terms of both water quantity shortage and unsuitability of water quality for sector specific uses.

The Meuse and Rhine basins are inhabited by about 9 and 50 million people, respectively, and are one of the most densely populated areas of western Europe. Furthermore, these rivers serve as a drinking-water source for respectively 6 (Meuse) and 30 (Rhine) million people (Houtman et al., 2013).

Event comparison in respect to drought hazard

- Index used for comparison of the 1976- and 2003-streamflow drought is number of days with streamflow less than 5-percentile streamflow.
- Comparison on water quality based on comparison of statistics (mean, median, minimum and maximum) in concentrations for both events compared to surrounding reference years.
- Diverse set of water quality parameters studied: general water quality parameters (i.e. water temperature, dissolved oxygen, pH, suspended solids, chlorophyll-a), nutrients, conservative substances, heavy metals and metalloids.

Event comparison in respect to exposure

Both the 1976 and 2003 droughts resulted in deterioration of water quality in the Meuse (Dutch part) with respect to water temperature, eutrophication, major elements, some heavy metal and metalloids. Water quality deterioration was strongly driven by declines in the dilution capacity for (point-source) effluents.

Water temperatures were also higher during droughts because of lower thermal capacity, increasing the sensitivity to atmospheric warming and reduced dilution capacity for thermal effluents from thermoelectric power plants (van Vliet et al., 2011). While higher temperatures overall resulted in lower mean and minimum dissolved oxygen concentrations, the peaks in dissolved oxygen (during day-time) were also higher during both droughts and in particular during the 1976 drought. These dissolved oxygen peaks corresponded with peaks in chlorophyll-a and pH and are likely related to algae blooms, in particular for the 1976 drought when dissolved oxygen concentrations reached supersaturation.

For nutrients, higher concentrations were found for ammonia, nitrite and ortho-phosphate during both droughts, mainly related to reduced dilution capacities and increased release from sediment under stagnant conditions. The nutrient concentrations were about three times higher during the drought (and surrounding references years) of 1976 than of 2003. This reflects the effects of pollutant emission reduction measures (e.g. construction of water treatment plants) over the period of investigated droughts. Concentrations of conservative substances (e.g. chloride, fluoride, sulphate) and some metalloids (e.g. arsenic) also significantly increased during both droughts as a result of lower dilution capacity, with highest concentration increases (and absolute concentrations) for the 1976 drought (van Vliet and Zwolsman, 2008).

Event comparison in respect to vulnerability

Several sectors are vulnerable to deterioration of water quality during droughts, including irrigation (e.g. exceeded salinity), power generation (water temperature) and drinking water production (several water quality parameters).

While less information on the water quality impacts for sectoral water uses are reported for the 1976 drought, than for the 2003-drought, some comparison can be made.

For the Meuse at station Eijsden, this can be done by evaluating the water quality impacts in relation to the Netherlands Drinking Water Directive (in Dutch (Waterleidingsbesluit, accessed 2020), which came into force in 1960. Our analyses show that during almost the entire drought periods of both 1976 and 2003 the drinking water threshold for ammonia was exceeded. In terms of salinity (chloride concentrations), the drinking water directive was temporally exceeded in particular during the 2003 drought, and increased treatment was therefore needed to avoid violation of standards.

For the whole Rhine-Meuse delta in the Netherlands, several water quality impacts during both droughts were reported, such as salinity intrusions under lower flow resulting in increased agricultural costs by 10% in western part of the Netherlands (2003). Increased concentrations of several pollutants (e.g. pesticides) resulted in exceeded drinking water guidelines, and hampered the inlet of Meuse water for drinking water production for two months in summer of 2003 (Juhasz-Holterman, 2004). The Dutch drinking water company WML discovered unknown substances in the Meus water (nearby Eijsden) during low flow. A conflict arose between WML and the Dutch chemistry concern DSM discharging waste water to the Meuse, because WML had to stop surface water extraction and was forced to pump more expensive groundwater to meet the drinking water demands. During the drought of 1976 also water quality problems for drinking water uses were reported in particular for chloride, while the drinking water demands increased by 7% (EDC, accessed 2020).

Increased water temperatures combined with low river flow resulted in reduced production capacities of thermoelectric power plants in the Netherlands with local declines in electricity production due to a lack of cooling water (Rübbelke and Vögele, 2011). This situation for the energy sector was most critical during June-September 1976 and August 2003 (EDC, accessed 2020; RWS, 2004)

In 1976, there were 150 hours load shed, while in 2003 this was even 650 hours load shed (EDC, accessed 2020). During the drought of 2003, emergency exemptions from environmental legislation were granted for several power plants in the Netherlands to ensure security of supply (avoid disruptions). Some of these emergency exemptions were also applied to two large industries in the Netherlands (Hoogovens Velsen, Shell-Moerdijk) in 2003 to avoid large disruption due to the high river water temperatures in 2003 (EDC, accessed 2020). A strong relation was also found between observed water temperature increase and reported electricity exchange prices (Boogert and Dupont, 2005) during the drought of 2003. The average electricity prices increased in a couple of days from 46 Euro/MWh to 373 Euro/MWh based on data of Boogert and Dupont (2005).

Water quality changes also resulted in adverse impacts for ecosystems during both droughts. For the 1976 drought, increased mortality of fish and other aquatic species were reported and many birds contract botulism due to low water quality (60,0000 cadavers were counted). Botulism and increased mortality of freshwater fish and mussle species were also reported for the 2003 drought, but it was difficult to state a causal link to the high water temperatures (EDC, accessed 2020).

Summary

The droughts of 1976 and 2003 resulted in strong declines in streamflow in the Meuse and Rhine basin and deterioration of water quality in the Netherlands with respect to water temperature, eutrophication, major elements, some heavy metal and metalloids. On average higher pollutant concentrations and overall stronger impacts of the drought on water quality were found for 1976 than 2003, which is in line both with the longer duration and higher persistence of the 1976 drought and with the effects of pollutant emission reduction measures (e.g. construction of water treatment plants) between the selected drought periods. Emission-reduction of point sources during low-flow conditions would reduce the adverse effects of droughts on surface water quality.

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Paired drought events: 1972-1977 and 2007-2017 droughts in the Don River catchment in Russian Federation

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Short description of both events with a focus on impacts

The main economic losses in the Don River basin (at village "Belyaevsky" - last cross-section before Tsymlyanskoe reservoir; study area description: see below) in the last 50 years are associated with droughts. The region is located in a zone of insufficient moisture, where dry years are typical phenomenon. The most extreme low-flow periods are 1972-1977 [1, 2] and 2007-2017. [6, 7, 8]. The driest years inside them were 1972 [1] and 2010 [8].

Scenarios of droughts in 1972 (and in 1975 as well) and 2010 are generally similar [1, 2, 8]. In these cases, both meteorological, soil and hydrological drought were recorded. The impact of droughts in both cases was complex. Arid conditions led to wild fires and deaths, according to [4], 60 people died from fires in 2010, 2.5 thousand families were left homeless. Another negative (including death), but indirect consequences were exacerbation of cardiovascular and bronchopulmonary diseases [4]. In 1972, 104 people died as a result of wild fires, thousands of USSR residents were left homeless [16-18]. According to the information given in [4], mortality rate in July 2010 in the European part of Russia increased by 50%, a surge in mortality was recorded in the summer of 1972 [16-18]. According to [17] there were close to 11,000 excess deaths from nonaccidental causes during this period, mainly among those older than 65 years.

Electric power generation was noticeably reduced at Tsimlyanskaya hydroelectric power station, in 2007-2017, capacities were used only by 30% [3], presumably in 1972 - 1977 the situation was similar (but no information is available). In 2010, due to low water levels, under the worst-case scenario, there could be a threat to drinking water supply to cities located mainly below the Tsimlyansk reservoir (about 20 to 30 cm remained to the critical mark of water withdrawals) - at Volgodonsk town, Rostov-on-Don city, Taganrog town [11]. However, at the end of the season, no restrictions on drinking and industrial water supply were introduced [11]. This was achieved thanks to the competent redistribution of resources, the depletion of multi-year reservoir capacities of the entire water management system in the Don basin. Due to the low levels in the conditions of the south wind direction, a deep penetration of salt water from the Taganrog Bay of the Sea of Azov was recorded 30–40 km upstream [11]. According to news reports [15, 19] tap water had a salty taste. Most likely, similar problems were in 1972-1977, they were simply not reported for Soviet ideological reasons.

During the 2007-2017 drought, a record algae blooming of the Tsimlyansk reservoir and the Don River was recorded. Algae concentrations exceeded the average values by 3-5 times [7]. Low flow adversely affected the reproduction of fish communities. In a study [7], it was shown that the number of yearlings directly depends on the water levels in the Tsimlyansk reservoir. For the drought period 2007-2017 the number of yearlings decreased by 2 times [7]. Low levels in 2007-2017 led to damage to navigation in the Lower Don, due to shallows the vessels were forced to go with underload 40% (data on 2010) so that the ship draft was less than 1.5 m [11]. No information on this was available for the 1972-1977 event.

Additional information: scenarios of drought development in 1972 and 2010

In 1972, arid conditions began to form even in winter, in January-February there was a little snowy and cold winter. Temperature anomaly was about -3…-4 degrees, and the amount of precipitation was less than 20% of the normal [1]. Very deep freezing of the soil was observed (up to 2 m). This damaged winter crops. Finally, 10.4 million hectares of winter crops were sown second time in the spring [1]. In the spring-summer period, the west-east air flow was disrupted, and the meridional (from south to north) type of circulation was established. In most of the European part of USSR, warmer temperature regime was observed already in March. In the following months, the positive anomaly began to increase. Already at the end of May, in some places the temperature passed over the mark of +30 degrees [1]. In the Don basin in June - July, the temperature deviation from the norm was + 2.4-2.8 degrees, and in August +5 degrees [1]. The anomaly was also expressed in the amount of precipitation. In the second decade of April, their number was less than 5 mm; dry winds and dust storms were observed throughout the region for 4-7 days [1]. They continued throughout the month of May, since the relative humidity was below 30% for 20 days or more. In total, the amount of precipitation for May-June was 40-60% of the norm [1], and for July-September it was 50-80%. The duration of the rainless period in the Don basin was 40-70 days [1]. The drought reached its peak in August in places, not a drop of rain fell, in the Chernozem region and Central regions the soil temperature reached 45-55 degrees, the fire of peat bogs and forest fires began. By autumn, the entire region was in the zone of drying of the arable layer (productive moisture reserves of less than 10 mm). By mid-summer, a lack of productive moisture in the soil (less than 10 mm) was observed over a vast territory, and the soil temperature in July reached 22-28 degrees [1]. The yield of winter and spring crops, potatoes, sugar beets were damaged. The drought swept not only the Don basin, but almost the entire Russian Plain from the western borders to the foothills of the Urals and from the Leningrad Region to the lower reaches of the Volga [1].

The 2010 drought scenario is generally similar to the 1972 drought. Severe atmospheric drought began to develop on a vast territory in May. The first signs of drought formed in the fall of 2009, when the moisture rates in the soil during fall decreased by 15-20% of the norm [4]. The depth of freezing of the soil was 30–50 cm greater (60-80 cm) than the mean annual values (30 cm) [4]. Because of this, during the period of snow melting, which developed rapidly, the unproductive surface runoff was quite large, and the replenishment of soil moisture reserves was insignificant. These phenomena were associated with the formation of a stable anticyclone, impaired west-east transport of air and stable advection of superheated air from Central Asia. Under the influence of these factors, the rapid evaporation of melt water and the drying out of the soil took place. In the first ten days of May, the reserves of productive moisture in the soil were 20–30 mm [4], but the steady high temperatures (28–30 degrees) had a negative effect on winter crops. The development of crops accelerated and was ahead of the average time by 10-15 days [4]. Already in early June, the reserves of productive moisture amounted to 3–9 mm, and in July - 0–8 mm [4]. The number of days with dry winds in May reached 17 [4]. In early June, the air temperature began to regularly overcome the mark of 33-36 degrees, the temperature anomaly for June was +2.9-4.4 degrees, for July - +5.7 - 7.0 degrees, for August -

+5.4 - 6, 4 degrees [4]. Thus, the peak of the dry period in the Don basin was the second decade of June. Moreover, the amount of precipitation was also significantly below normal. On average, 85% of the norm fell in the Don basin in May, only about 30% in June, and about 40% in August [4]. In some areas, the duration of the rainless period was more than 20 days [4]. Soil drought in various subjects of the Russian Federation in June covered from 40 to 70% of the areas occupied by grain crops [4]. As a result, crops on an area of about 10 million hectares - died [4]. Drought covered more than half of the area of European Russia.

Descriptions of processes between events with a focus on risk management

Between 1972 and 2010, significant economic and social changes occurred in the country and in the Don basin. First of all, in 1991, the collapse of the Soviet Union and the creation on its territory of few independent countries took place. This entailed a severe economic crisis, which led to a sharp drop in industrial production, a decline in agriculture, including water management. After the collapse of the Soviet Union, water consumption in the Don basin decreased from 12934 million m^3 in 1990 to 4134 in 2015 [6]. The main surface water consumer in the Don basin (average for 1991–2014) is industry (63%), followed by irrigation (20%), drinking water supply (5%), fisheries (5%) and other needs [6].

Agricultural development in the regions of the Don River basin relies primarily on the use of high fertility of chernozems, and in the southern regions of the basin - on the intensification of irrigated agriculture. In general, in the 20th century, irrigation areas in Don River basin gradually increased and by 1990 reached 1.15 million hectares of irrigated and 67.7 thousand hectares of drained land [6]. However, after the collapse of the USSR, by the beginning of 2008, the area of irrigated lands in the Don basin decreased to 465.4 thousand ha, and of drained land - 35.4 thousand ha, which, respectively, amounted to 40.3% and 52.3% of the 1990 level [6]. Use of water resources for irrigation for period 1990–2015 compared with the 1990 level, decreased by 4 times [6].

Despite the economic crisis of the 1990s, changes in the area of arable land in the Upper and Middle reaches of the Don River (to the Kazanskaya cross section) decreased slightly, on average, a decrease of 6% [8, 9]. The land use structure has also changed in some way. In the 1970s, autumn plowing was widely used in the Don basin. The share of such fields reached 40-50% [8, 9], at present due to the replacement of spring crops with winter crops, the area autumn plowing decreased in different regions by 1.5 - 2.5 times. During the period from 1972 to 2010, floodplains overgrown, the forest area increased on average by 5%, from 1 to 5% in the Upper Don and from 10 to 15% for its left-bank tributary - Khoper. The increase in the share of urbanized territories reached 2.5% [9].

The processes taking place in Russia from 1972-1977 to 2007-2017 significantly affected the distribution of the population. In recent decades, there has been an intensive migration of the rural population to cities; according to [6], the share of urban population for all regions of the entire Don basin exceeded 50%, averaging 64%. In 1972, this indicator was 2 times lower [6]. The total population of the regions partly and fully located inside Don river basin according to State Statistical Reports (2011, 1973) characterized by slow decrease. For 1.01.1972 total in the basin 11856 ths people live in the area, and on 01.01.2010 it was 11805 ths. Inhabitants.

The Don basin is poor in terms of hydropower. The Tsimlyansk reservoir and Tsimlyansk hydroelectric station were put into operation in 1952 [6]. The installed capacity of the hydroelectric power station is 204 mW, but since 1970 the station has been switched to forced operation. This means that the average daily costs of hydropower plants are determined by water releases for non-energy participants in the water sector and maintaining the ecological flow of the Don River [6]. The main problems of water management that arose from 1972 to

2010 are associated with the inadequate condition of irrigation systems and the large losses of water in them. The media and individual studies [6, 19] talk about the emergency condition of many small ponds and reservoirs, most of which are silty and running in "open mode".

From the risk management point of view - there is no information about this for 1972. Presumably no early forecasts and measures to cope with drought were undertaken at that time. Since 2004, in Russia on the basis of the All-Russian Research Institute of Agricultural Meteorology, founded in 1977 after the arid 1972 and 1975, there is a Drought Monitoring Center [20]. From May to September, the Institute's website hosts bulletins for monitoring agrometeorological conditions with a temporary resolution of 10 days, and drought indices are calculated. Based on the analytical data of the center, management decisions are made. During the spring sowing season in 2010, due to bad conditions, several special references were prepared for farmers, and in June the Ministry of Agriculture prepared a detailed analytical report on agrometeorological conditions, the current drought and its distribution area. Thus, with a lead time of 1-1.5 months, abnormally dry conditions were predicted during the ripening period of the crop, and corrections were made to the forecast of the yield [4]. In July 2010 The Working group was created to implement a set of activities aimed at overcoming the effects of drought [4]. As part of this work, weekly reports were generated on the current conditions and forecasts (for 10 days). In addition, at the beginning of August, the optimal (later) dates of sowing winter crops for the 2011 harvest were calculated [4].

Event comparison in respect to drought hazard

Indices for meteorological, soil moisture and/or hydrological droughts[1]: threshold-based indices giving duration and severity of drought in precipitation, soil moisture, river discharge, groundwater, lakes, and/or reservoirs, or duration and severity from standardized precipitation index (SPI), standardized precipitation evaporation index (SPEI), soil moisture anomaly (SMA), standardized groundwater index (SGI) and/or standardized runoff index (SRI) (potentially with a figure providing an overview of both events, in time and space)

Meteorological drought

Standardized SPI and SPEI indices are used to assess the dangers of meteorological droughts. Figure 2 presents graphs of indexes with a moving average for 3, 6, 12, 24, 36, and 48 months.

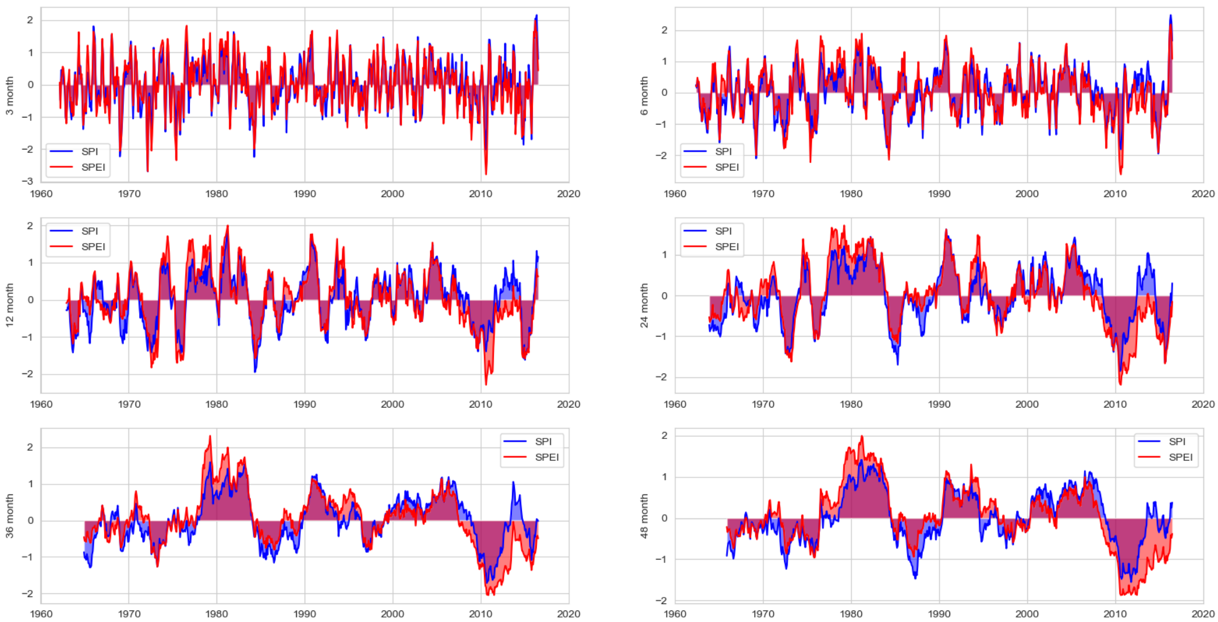

Fig. 2 Indices SPI and SPEI for the Don River basin at village Belyaevsky

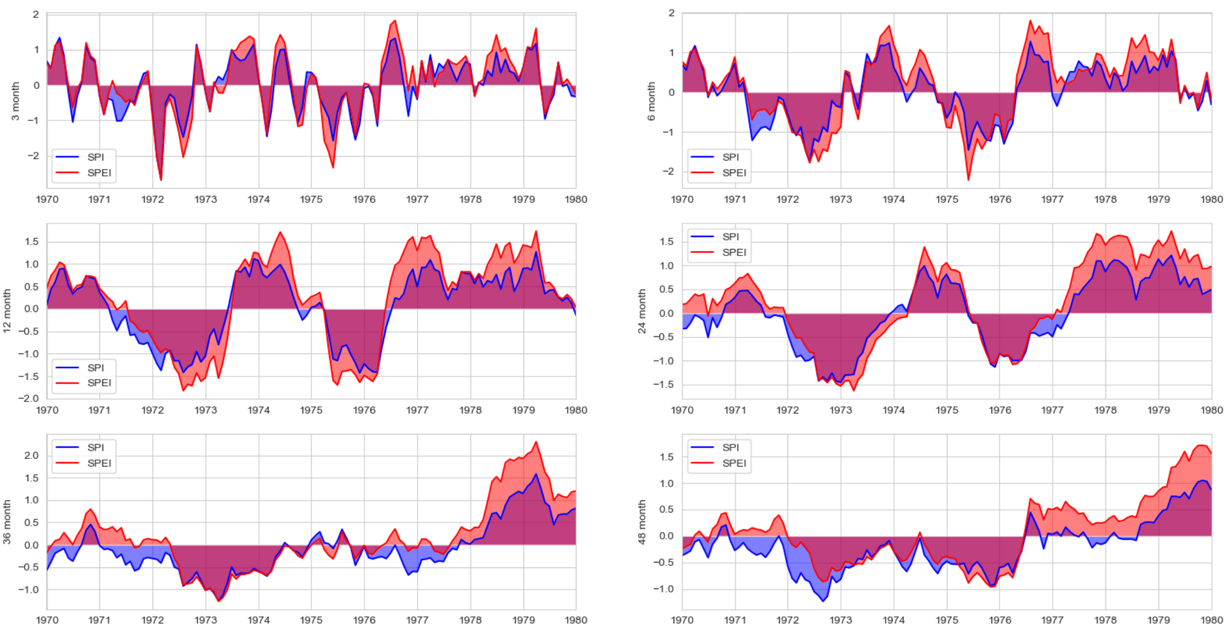

Fig. 3 Indices SPI and SPEI for decade 1970-1980 for the Don River basin at village Belyaevsky

Based on the graphs, a dry period is distinguished from the beginning of 1971 to the middle of 1976, with a total duration of 5.5 years. The average value of the indices SPI_12 and SPEI_12, for the entire period is -0.37 and -0.36, respectively. Two years with increased humidity (1973 and 1974) are distinguished within the dry period, the indices SPI_12 and SPEI_12 for which are 0.59 and 0.84, respectively (0.33 and 0.4). The indices SPI_12 and SPEI_12 for 1971-1972 are respectively -0.73 and -0.78, for 1975-1976 SPI_12 = -0.83 and SPEI_12 = -1.

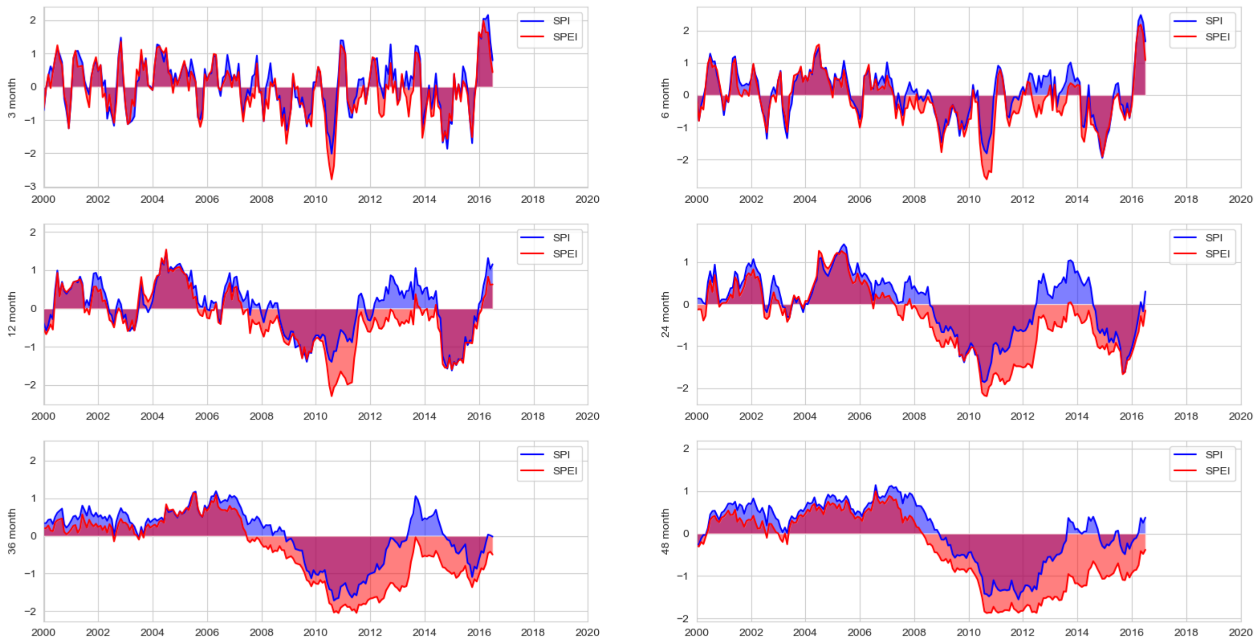

Fig. 4 Indices SPI and SPEI for decades 2000-2020 for the Don River basin at village Belyaevsky

The graphs also clearly show the dry period of recent years: from 2008 to 2016, with a total duration of 9 years. The average value of the indices SPI_12 and SPEI_12, for the entire period is -0.29 and -0.72, respectively. Within the dry period, 2 years are distinguished (2012 and 2013) with humidity close to long-term values: SPI_12 = 0.42 and SPEI_12 = -0.27. The indices SPI_12 and SPEI_12 for 2008-2011 are respectively -0.61 and -1.02, for 2014-2016 SPI_12 = -0.34 and SPEI_12 = -0.59.

The meteorological drought of recent years is longer and deeper than the drought of the 70s. An interesting feature of the drought of 2008-2016 is a strong role of evaporation as a consequence of the increase in the average annual temperature by 1-1.5 degrees, as can be seen from the difference between the SPI and SPEI indices. Within both meteorological droughts, there are several years with long-term mean values that somewhat reduce the effects of the droughts of previous years. However, the increased role of evaporation during the drought period of 2008-2016 significantly reduced the effectiveness of filling deficits with a series of years of average water availability.

<u>Hydrological drought</u>

The SRI is used to determine hydrological droughts and their severity. In Figure 5, two dry periods can be distinguished: from the second half of 1971 to the end of 1976 (total duration 5.5 years) and from 2009 to 2016 (total duration 8 years). Low water period 1972-1976 was one of the strongest in the history of observations, and 1972 and 1975. - The driest years during this period. So for 1972, the average value of the index SRI_12 = -1.83, while the minimum (during the year) reaches -2.5. For 1975, the average value of the index SRI_12 = -1.08, the minimum (during the year) is -1.85. Moreover, if we generalize the data for the combined low-water period, then the average value of the SRI_12 index for 1972-1976 is -1.12.

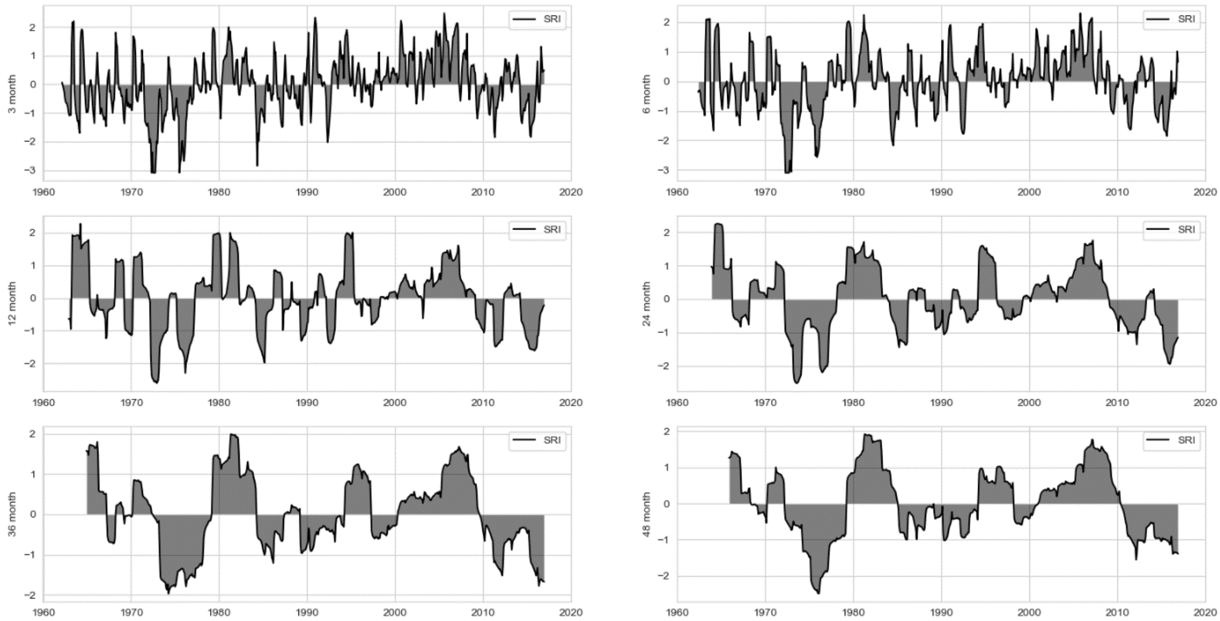

Fig. 5 Index SRI for the Don River basin at village Belyaevsky

Low flow period 2009-2016 is the longest, but at the same time, not the most severe. If we consider each year of this period separately, then we cannot say that they are extremely low flow. From the entire dry period, according to hydrological data, we can distinguish 4 most dry years (2009, 2011, 2014 and 2015), which alternate with 4 years with discharges close to average (2010, 2012, 2013 and 2016). The decisive factor in this hydrological drought was its duration, which amounts to 8 years. On average, for the period 2009-2016, the SRI_12 index is -0.63, and for the "core" of low water (2014-2015), SRI_12 is -1.07.

In the Don basin, water levels below the minimum for the summer low water period were noted in 2007-2017: r. Don v. Gremyachje - level decreased to -145 cm, which corresponds to the minimum for the observation period (1972), r. Don near the town of Liski, the decrease in the level was –138 cm, which is below the minimum level by 12 cm (-126 cm in 1972), r. Vorona (main tribytary of Khoper) near town Borisoglebsk had a water level of -56 cm (-15 cm minimum for the observation period) and persisted for 13 days [11].

According to the data given in [5], runoff in 1972 (the driest year during 1972-195 drought) was estimated as 95-99 percentile of long-term records, that means return period 1 time in a century. According to the calculations made in [7, 6] for 2010 (the driest year during 2007-2017 drought) runoff was about 97-98 percentile of long-term records in Lower Don and 75 percentile of long-term records in Upper Don.

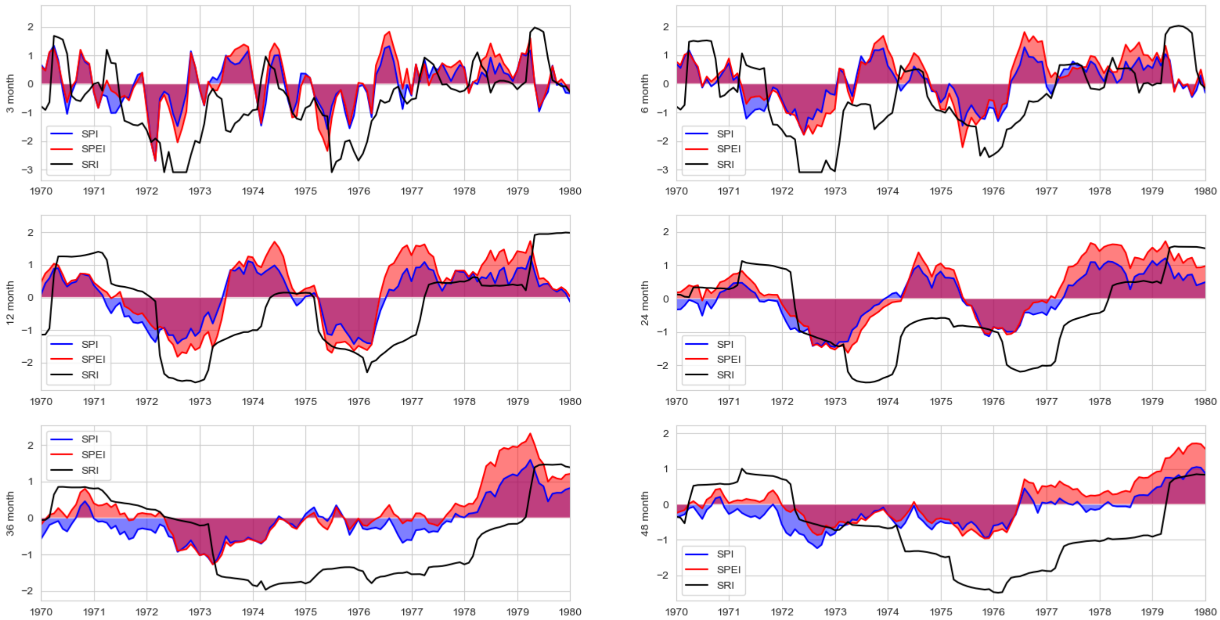

Fig. 6. Comparison of the SRI, SPI and SPEI indices, 1970-1980 for the Don River basin at village Belyaevsky

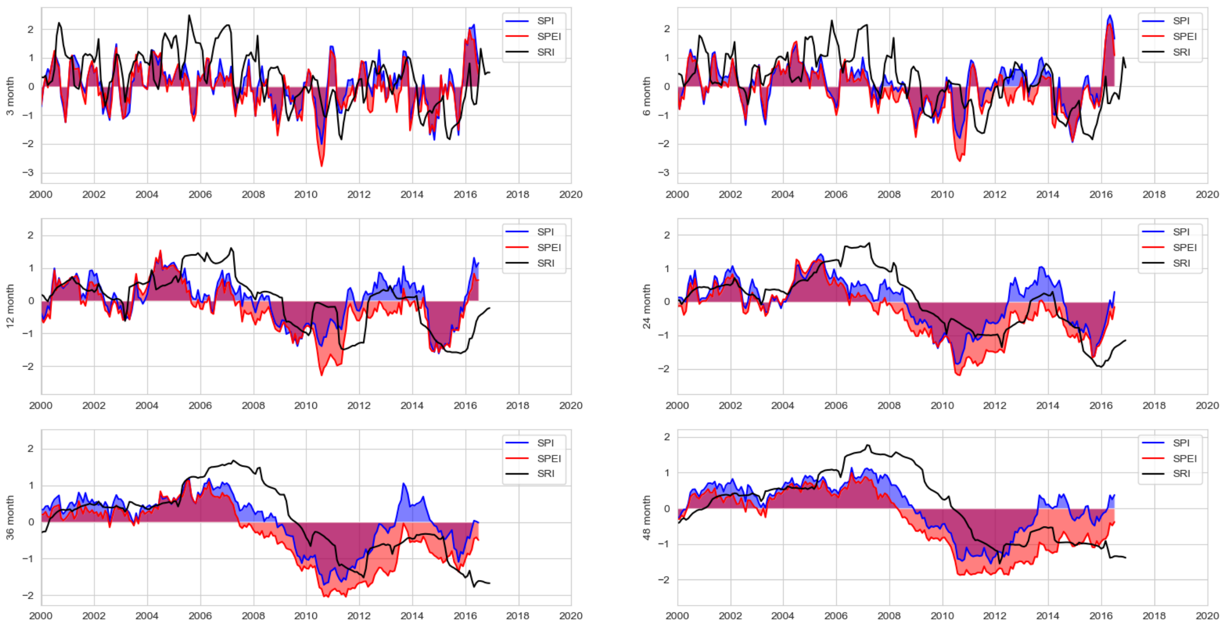

Fig. 7. Comparison of the SRI, SPI and SPEI indices, for 2000 – 2016 for the Don River basin at village Belyaevsky

When comparing meteorological and hydrological droughts with each other (Fig. 6-7), one can notice a certain delay in the hydrological drought (about six months), arising due to the presence of buffer moisture reserves in the catchment. The Don basin has a large catchment capacity and low groundwater table: in the southern parts of the basin, the first ground horizon is located 20-30 m from the surface. So, for example, dry summer has little effect on river flow during the same period, however, the deficit of moisture that has arisen in the soil and soil horizons will be replenished in the spring during floods, thereby increasing its loss. Also, after a prolonged meteorological drought and the beginning of the “wet period”, inertia is observed when the river flow is “restored” to normal values. This delay occurs due to the fact that most of the rainfall is spent on covering the existing moisture deficit in the surface and subsurfase watershed, which can take quite a lot of time, in some cases the delay can reach up to one year.

The low flow period of the 70s can be described as a very deep, but at the same time characterized by rather short negative flow anomaly. While the low flow period of the 2000s is a long series of years with relatively small deficits of water resources. However, if we compare 2 dry periods with each other in terms of total deficits of water resources, it turns out that the deficit for the period 2009-2016 is almost 30% greater than the deficit for the period 1972-1976.

Soil drought

As a criterion characterizing soil drought, the Palmer Index PDSI is used in this work. For the Don Basin catchment, the available water capacity was assumed to be 150 mm. Based on PDSI, two of the driest periods can be distinguished (Fig. 8): 1971 - early 1976 (total duration 5.5 years) and 2007-2015 (total duration 9 years). The period 1971 - beginning of 1976 is characterized by two deep intermittent droughts (1971 - mid 1973 and mid 1974 - early 1976), the average PDSI index for which is respectively -0.97 and -1.4, the minimum PDSI values reach respectively -3.7 and -3.5. On average, during the period 1971 - early 1976, the PDSI index is -0.68. Drought 2007-2015 was characterized by a permanent lack of soil moisture throughout the entire period. The average PDSI index for the entire period is -1.08. And from the point of view of soil drought, the period of the last low water is the most severe. The driest year was 2010, with an average PDSI of -2.43 and a minimum of -4.8 during the year, making it the driest over the entire observation period. Undoubtedly, the soil drought of recent years is much stronger than the drought of the 70s. The total moisture deficit that arose during the period 2007-2015. 2.5 times more drought deficit of the 70s.

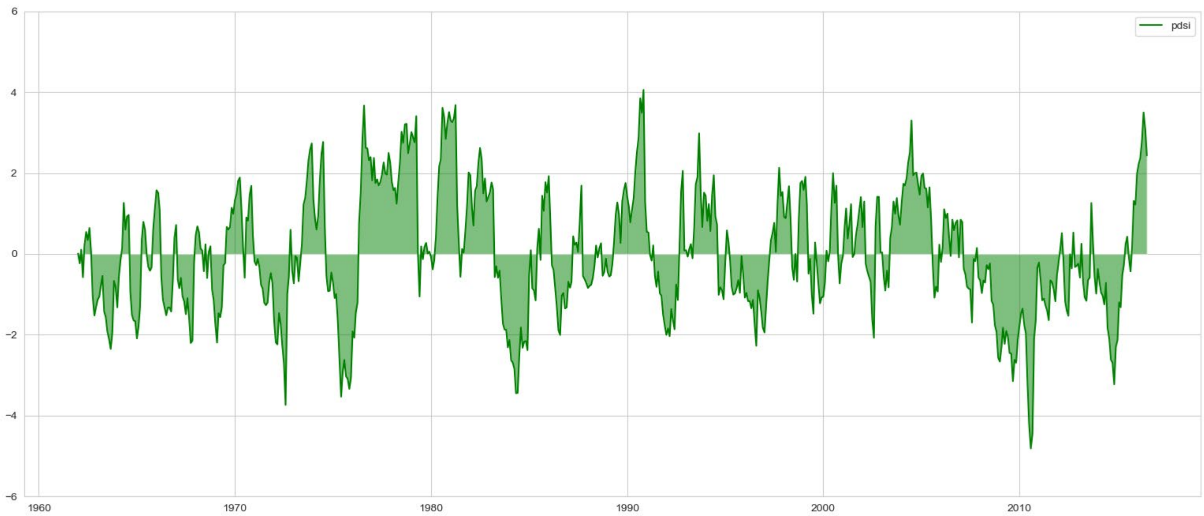

Fig. 8 Index PDSI for the Don River basin at village Belyaevsky

Ground water levels during drought periods

The analysis showed that the use of the SGI index based on data on average annual groundwater levels of the Kamennaya Steppe water-balance station is not advisable due to the non-stationary of the time-series and the presence of a positive trend in groundwater levels since the mid-1950s. The lowest groundwater level at the Kamennaya Steppe water-balance station was recorded in 1939 and amounted to -8.07 m from the surface. Then there was a growth trend, which was interrupted by wet years (1941-1945). Then, in 1956, bent water levels again fell to a level of -7.56 m from the surface, presumably these were the consequences of a series of dry years (1952-1953). Since then, a steady, statistically significant positive trend has been observed in the level fluctuations.

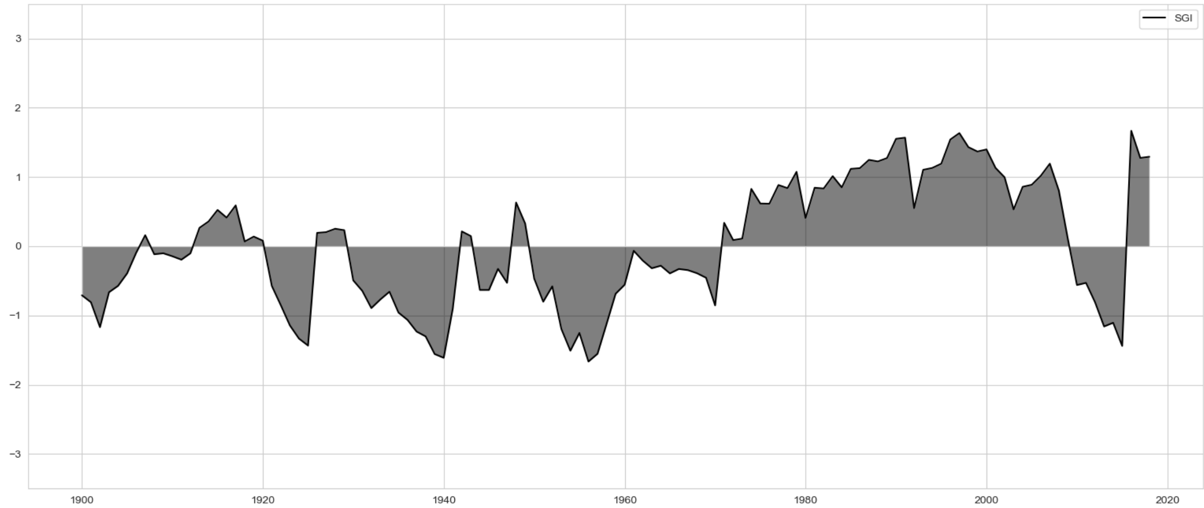

Fig. 9 SGI Index for Groundwater Levels at the Kamennaya Steppe Water Balance Station

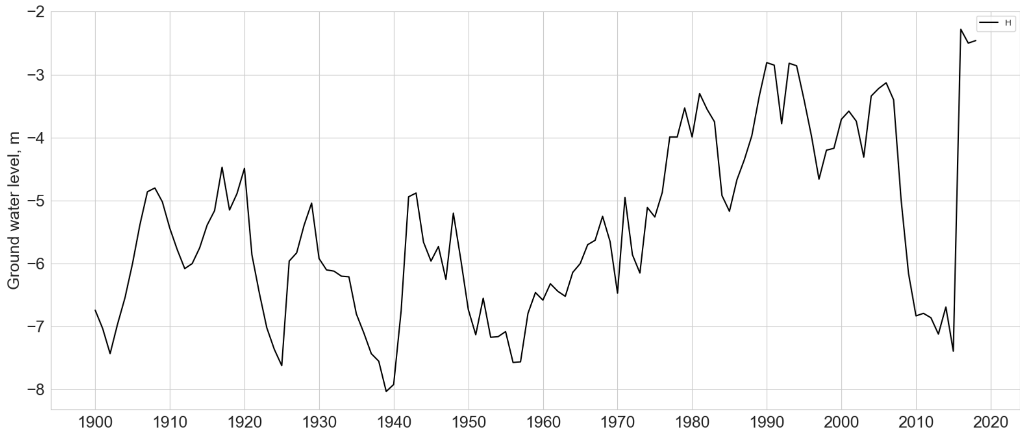

Fig. 10 Groundwater levels at the water balance station Kamennaya Step

Deficits in the Tsymlyansk reservoir and Lower Don

Periods of low flow were strongly reflected in the fluctuation of levels in the Tsimlyansk reservoir. Based on special schedules and data on water discharges from the hydroelectric station, deficits were calculated for water users of the Lower Don (site after the reservoir). In 1972, there was a colossal shortage of water resources in the lower reaches for the water year (March-February), the flow rate amounted to only 46.6% of the normal estimated. In September 1972, water levels in the reservoir dropped below the design level of ULV, levels below the design level remained until March 1973. Drought also affected the discharges of the next year, 1973, when the volume of discharges amounted to 67% of the norm. In 2010, the picture was slightly different. The drought led to a significant depletion of long-term water reserves accumulated in the Tsimlyansk reservoir in previous years. Due to the optimal management regime, water shortage was noticeably smaller and occurred only in 2011 (discharge was 88.1% of the norm).

Event comparison in respect to exposure

Comparing two events in terms of their impact on the economy is an extremely difficult task in view of the socio-economic differences between the Soviet and post-Soviet periods. In addition, most damage statistics in Russia are provided in open sources for the entire territory of the country, without dividing it into regions and entities. According to estimates given in studies [1, 4], the area covered by drought in 1972 was about 1000 thousand km^2, the northern border of the drought reached 60 degrees N, the eastern border was limited to the Ural Mountains (58 degrees east longitude). In 2010, the northern border of the drought reached 58 degrees north latitude, the drought did not occur in the northwestern regions, but significantly advanced beyond the Ural Mountains, covering the south of Western Siberia up to 67 degrees east longitude. According to rough estimates, the area covered by drought in 2010 amounted to about 900 thousand km^2 [4].

In 2010, at the end of January, the death of winter crops was predicted on an area of 2 million hectares in the European part of Russia [4], in 1972, the death of winter crops covered an area of 10.4 million hectares in the European part of Russia [1]. In general, during the summer period, agriculture suffered enormous losses, in 1972, due to burnout and death of the grain harvest, it was necessary to purchase up to 40% of the total required grain volume [1]. Producers of sugar beets, corn, potatoes and other vegetables were affected. The productivity of cereals and legumes throughout the Russian Federation as a whole during the years of severe droughts is reduced by 16-25%. The lowest yield indicators were in 1975 (6280 kg / hectare) [4], in 1972 the values were about 8600 kg / hectare due to optimal conditions in the spring, before the drought began [4]. In 2010, the decrease in yield according to [4] was from 17 to 46% in the regions of the Don basin in relation to the previous year. The precipitation deficit in June-July 2010 was the most significant in the history of meteorological observations. In November 2010, 43 regions of the Russian Federation were recognized as affected by drought [4]. The death of agricultural crops occurred on an area of more than 13.3 million hectares [4]. Damage to agriculture from the drought of 2010 amounted to 41.8 billion rubles (in prices of 2010) [4]. In terms of agricultural losses, the 2010 drought is the most significant in the country over the past 60 years [4]. Drought-induced shortage of spring grain crops exceeded 50% of the 2008 crop level (the most productive year) in the Central, Volga and Southern Federal Districts. Gross grain harvest in the country for 2000-2009 amounted to 82.4 million tons [4]. In 2010, it decreased by 26% compared with the average and amounted to about 61 million tons. Compared to 2009, the yield of grain crops decreased even more - by 37% [4].

For the Lower Don in 2010, the duration of the water levels at the marks below which the safe movement of ships is impossible exceeded 100 days [4, 11]. In 1972 and 1975, due to low levels, navigation was completely stopped at the end of July [1, 5, 17] till next year.

The deterioration of water quality in the Don basin in 2010 was reflected in an increase in the number of samples with critical concentration exceeded by 30% [11]. In 2010, there was a threat of stopping the water supply station of the Belgorod Oil and Gas Power station [11]. The main reason is the inadequate technical condition of the water intake facilities designed and built at marks that do not meet regulatory requirements. It was possible to avoid the stop only thanks to direct work with the water user and the adoption of operational measures to regulate discharge from the Belgorod reservoir.

Separately, it should be said about the area of wild fires, in 1972 in the USSR 40 thousand forest fires arose on an area of 1,460 thousand hectares [18]. Smoke was observed in cities, in particular smoke stood in Moscow for several days [19]. To cope with fires, the military and forestry services were involved, in addition, residents independently organized public squads. In 2010, there were about 30 thousand wild fires with a total area of more than 1,246 thousand hectares [13, 15]. Cities of Central Russia were shrouded in smoke, the list included large regional centers, such as Nizhny Novgorod, Tula, Ryazan, Voronezh, Saratov, Tambov, Tver, Lipetsk, Tolyatti, Vladimir, Omsk, Cheboksary, Novocheboksarsk, Kazan. In Moscow, haze and smoke were observed for 23 days [15].

Event comparison in respect to vulnerability

In 1972, the Soviet Union did not have a system of warning the population about natural disasters, the media reported that voluntary squads were organized to combat forest fires, and the population was not notified [16, 18]. In the post-Soviet period, with the development of information technologies, early warning systems for droughts were significantly modernized and developed, and the Ministry of Emergency Situations was created, the activities of which are also aimed at early response and prevention of damage from natural and man-made disasters. As part of the work of Roshydromet, the MeteoAlarm program [21] was implemented, a drought monitoring center was created at the All-Russian Scientific Research Institute of Agricultural Meteorology [20], which was founded in 1977 after the dry years of 1972 and 1975. In the practice of runoff regulating and managing water resources in dry years, the Water Resources Agency [22] implements a number of measures. The weekly meetings on the work of a particular water management complex in a dry period usually organized. However, an open system for accounting risks and damages from droughts in Russia is still missing, if information about them is generalized, it is only within the framework of relevant ministries or institutions. Statistical reporting data are not published in the public domain and are not available for research. Also imperfect is the drought risk insurance system, which is voluntary.

Summary

Summing up, it should be said that the droughts of 1972 and 2010 are very similar, in both cases the main cause of the catastrophic phenomenon was an anomaly in atmospheric circulation associated with the processes of blocking the west-east transport of air masses and the advection of hot air from Central Asia to the north. Comparisons of various drought indices calculated according to international methods make it possible to assess the complexity and scale of the phenomena observed during these years. The graphs (Fig. 11, 12) show that the drought manifested itself in meteorological, agrometeorological and hydrological indicators, and was reflected in groundwater levels as well.

The consequences of both events entailed multi-billion dollar damage, which cannot be fully assessed due to the lack of reliable and accurate statistical information. In the Soviet period, the policy of “suppressing” information about natural disasters actually led to a complete lack of informing the population about catastrophic events. In post-Soviet Russia, specialized structures were created, including the Ministry of Emergency Situations, a warning system for meteorological hazards and natural fires, a methodological framework for analyzing agrometeorological conditions was developed, and seasonal and decadal weather and agrometeorological forecasting techniques were developed. In addition, the low flow period of 2010 received enormous publicity in the media, which certainly had a positive effect on alerting the public, informing about poor air quality, and the possibilities of preventive measures to maintain health. Nevertheless, the system of warning and accounting for natural hazards in Russia is far from perfect and significantly lags behind the developed countries of the European Union and the USA.

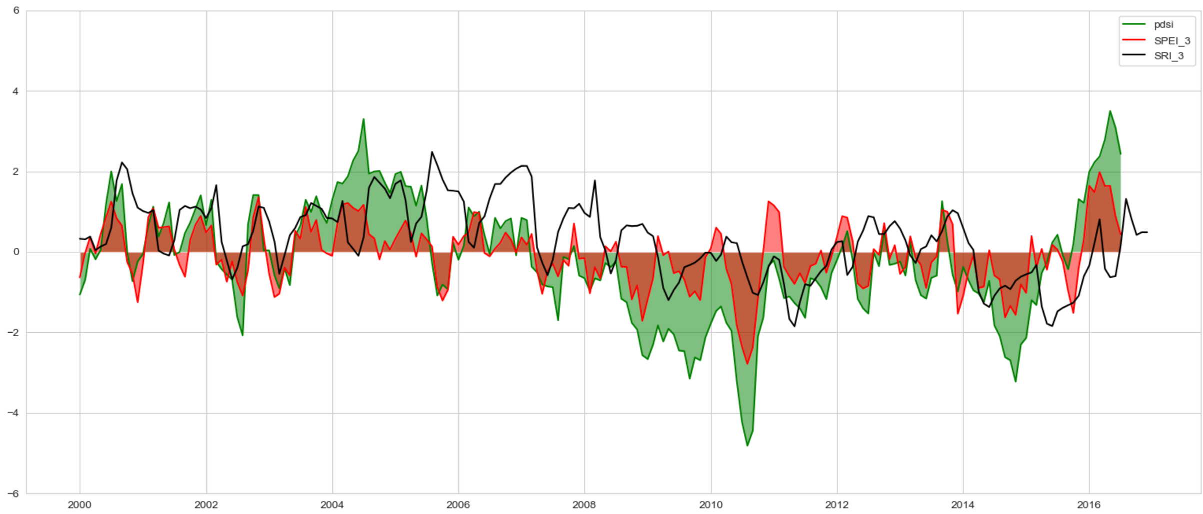

Fig. 11. Comparison of the indices SRI_3, SPEI_3 and PDSI, for 2000 – 2016 period for the Don River basin at village Belyaevsky

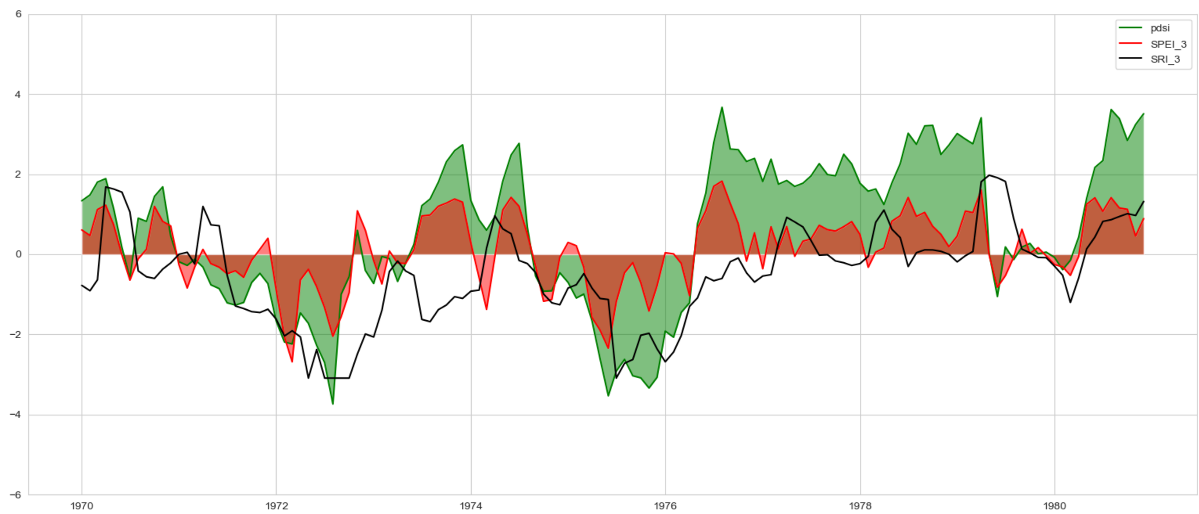

Fig. 12. Comparison of the indices SRI_3, SPEI_3 and PDSI, for 1970 – 1980 period for the Don River basin at village Belyaevsky

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The official website of the Don Water Basin Management http://www.donbvu.ru/

Study area

The Don River Basin is one of the most intensively developed regions of Russia, the coefficient of water use at the mouth is more than 0.4 [6]. This is one of the key agricultural regions of Russia, where more than 20% of cereals are grown in the Russian Federation [6]. Water resources are the key point for the region's economic well-being. The Don River basin plays an important role in the production of agricultural products of the Russian Federation. As a result, the anthropogenic pressure on this basin is very high. For example, we can say that in the Russian part of the basin, which occupies about 2.2% of the country's territory, the area of agricultural land is 32.2 million hectares, which is almost 15% of the area of all agricultural land in Russia [6]. It should also be noted that the total population living in the basin within the Russian Federation is about 12 million people, i.e. 8% of the total population of the country [6]. In addition, the Lower Don is the largest freight waterway from the basin of the Sea of Azov to the Black and Mediterranean and through the Volga-Don Canal to the Caspian Sea. On average, the volume of freight traffic in the Lower Don in 2001-2006 (before the period of drought) was 17.7 million tons [3].

The runoff of the Don has a decisive influence on the influx of water into the Sea of Azov and the state of the fish community. The average long-term natural runoff of the rivers of the Sea of Azov is about 41 km^3, including Don River about 28 km^3 [6]. Average inflow of river water into the sea in 1969–1976 was minimal - 25 km^3, and the salinity of sea water reached maximum values - 13.8 ‰. Between 1977 and 1982 river water inflow increased to 39.2 km^3, which led to a decrease in salinity to 10.9 ‰. Currently, the average runoff is about 24 km^3 and sea salinity is about 12 ‰ [6].

The river system of The Don provides reproduction of more than 60% of the stocks of migratory and semi-migratory fish of the Sea of Azov, as well as about 70% of Don fish. The basis of the high fish productivity of the Sea of Azov is favorable breeding conditions for migratory and semi-migratory fish in the Don River system. The area of spawning grounds flooded here in spring reaches an average of 95 thousand ha [6] with an average duration of flooding of 49 days [6]. The main breeding sites for semi-migratory fish are the delta of the Don River and Don river meadow in the lower reaches with a modern flooding area of about 60 thousand ha at a water flow rate of 2800 m^3/s [6]. Over the past decades, the landscape and hydrographic network of the Lower Don floodplain have changed as a result of economic activity and the filling of the Tsimlyansk reservoir at 1952. The probability of floodplain flooding decreased to 30–35% with sometimes interruptions up to 9 years [6]. As a result of runoff regulation 100% spawning grounds of beluga and 80% spawning grounds of stellate sturgeon, sturgeon, herring, bream, perch and other fish turned out to be cut off and inaccessible to mature fish[6]. In addition, small pond fisheries are actively developed in the Don basin.

For long-term and intra-annual flow regulation, in order to accumulate water reserves during the spring flood period for use during the low-water period, a large number of reservoirs and ponds were created in the Don basin (917 reservoirs, 8000 ponds and other regulatory structures for various purposes with the total volume of 31.8 km^3) [11]. The largest reservoir is Tsimlyanskoe with a surface area of 2702 km^2 and a volume of 23.86 km^3. The reservoir was commissioned in 1952 and is the largest water body in southern Russia, it carries out seasonal and multi-year flow regulation.

The calculations in this work were carried out for the cross-section Don River at village “Belyaevsky”. This is the last hydrological gauging station located above the Tsimlyansk reservoir and not experiencing its influence on the runoff distribution. The catchment area at the mouth of the riv. Don is 422 thousand km^2 [6], and in the village “Belyaevsky” - 204 thousand km^2 [6]. The drought indices were analyzed using data from all available in the archives of the All-Russian Institute of Hydrometeorological Information - the World Data Center [12] in the basin (52 stations in total, see Fig. 1), the values of temperature and precipitation were averaged over the area. To analyze the groundwater level, the data were used from the water-balance stations “Kamennaya Step” and “Nizhnedevitsk”.

Data about economic loss presented in the work in most cases apply to the entire river basin. Due to the lack of a system of statistical accounting of damages, it is not possible to calculate them for the allocated catchment. In some cases, the data given for damages throughout the European part of Russia since regional reporting is also missing.

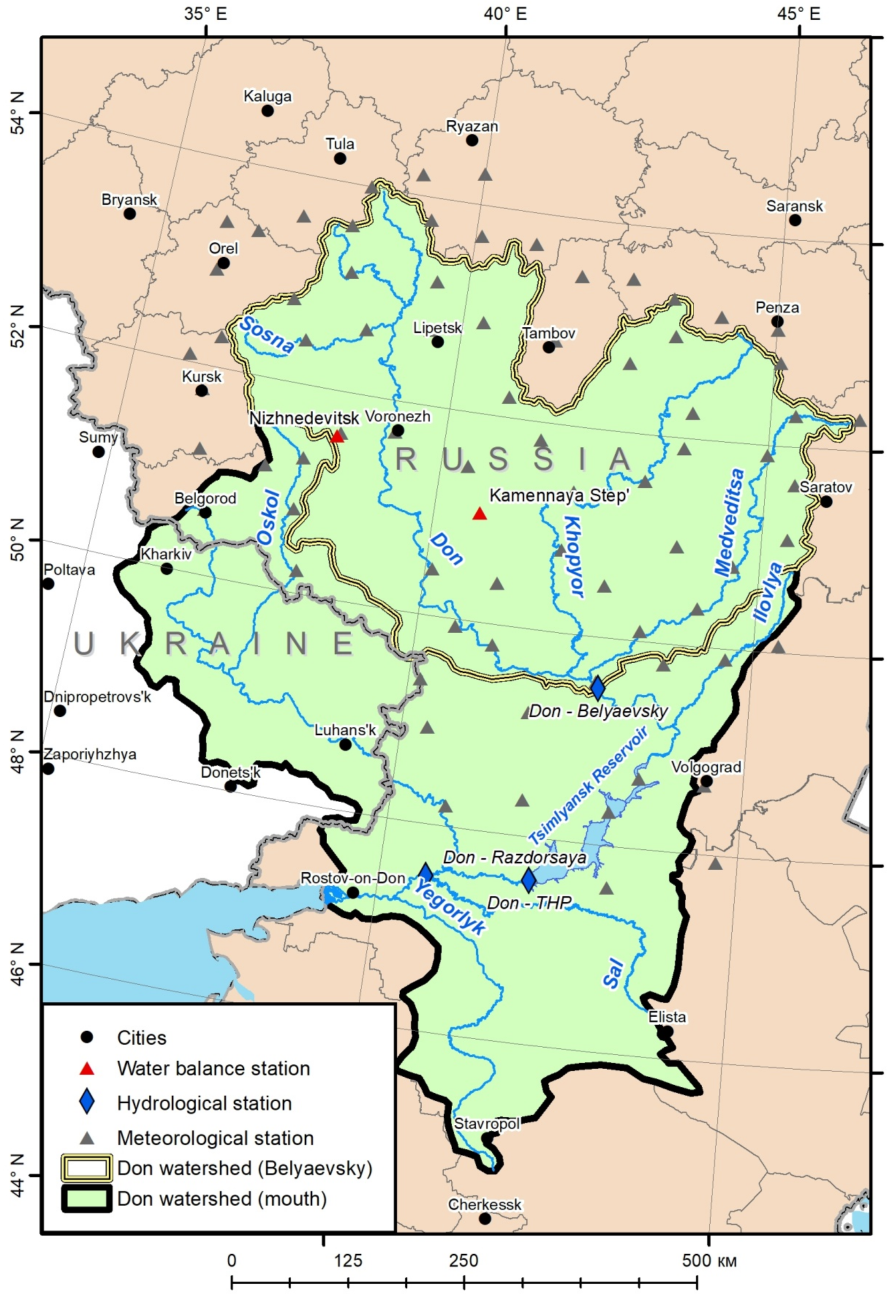

Fig. 1 The map of the Don river catchment and hydrological and meteorological stations used in this study

ID 26

Paired drought events: 1973 and 2014 droughts in the Seyhan River basin in the Mediterranean region of Turkey

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Short description of both events with a focus on impacts

Seyhan River basin in Turkey was seriously affected by drought in the years 1973 and 2014 in terms of meteorological drought causing significant negative impacts. These two years indicate paired drought events in Adana province (the Eastern Mediterranean region in southern Turkey). The first of the two drought events was newsworthy (web1) in the daily newspapers emphasizing that the agricultural activities stopped due to insufficient rainfall in the region. The second drought was observed due to the low precipitation in 2013 affecting also the year 2014. It has been indicated in the newspapers (web2) that it caused to reduce water level in the Seyhan River with more than 40%. Inhabitants in the river basin were affected by water shortages in cities, economic impacts, negative consequences on agriculture during both events. It could be important to mention that drought event in 1973 has mostly affected on the agricultural activities and energy sector while the second drought affected not only the agriculture and industry but also it heavily caused shortages in water allocated to the cities and urban areas in the region.

Descriptions of processes between events with a focus on risk management

Many studies have been carried out on water resources management and water use in the Seyhan River basin. For example, the Water Management and Preparation of Basin Protection Action Plans were completed by the Marmara Research Center (MAM) of the Scientific and Technological Research Council of Turkey (TUBITAK, 2010). Also, the General Directorate of Water Management under the Ministry of Agriculture and Forestry has performed future projections to protect, develop and efficiently use water resources by investigating the impact of climate change on water resources through the statutory decree dated 26.06.2011 (Sahin and Kurnaz, 2014). The General Directorate of State Meteorological Works of Turkey prepared a report on Drought Evaluation in Turkey to determine the precaution to be taken during the drought (MGM, 2014). The report states that the project called “1000 Ponds in 1000 Days” has been initiated by the Ministry of Forestry and Water (Ministry of Agriculture and Forestry now) to reduce the impact of drought on irrigation. Besides, the report covers several “conservation measures” to be taken against the management of drought risk and crisis, and provides further information related to the efficient use of water when there is no enough water (MGM, 2014, p.58).

During the 1973 drought, there was a lack of water infrastructure which was improved. The Regional Directorate of State Hydraulic Works (DSI with its Turkish acronym) is responsible for the Adana province in the Seyhan River basin. In the website of the regional directorate (web6, web7), it is indicated that, within the administrative border of Adana province, other than the Seyhan Dam (in operation since 1956), 14 more dams are in operation; 2 of which have been active in 1971 and 1972 before the 1973 drought, 8 in the years 2014-2016 after the 2014 drought. Another 4 dams have been active from mid 1990s to 2010 while another one is under construction. There are 2 ponds in Adana; one being active since 1999 another since 2014. Thirty-three irrigation systems have been listed, 18 before 2014, 15 in the period 2014-2018; 12 more not in operation yet. Based on the above listed water infrastructural development, it should be stressed that the Cukurova plain where the Seyhan River basin and the Adana province are located is at the high importance for Turkey in terms of agricultural production.

There was a lack of drought risk management aspects; i.e., no particular actions in terms of drought risk management were found for the 1973 drought. However, medium to high preparedness was provided, that is several conservation measures were established for the drought risk management before the 2014 drought event which are as follows:

Measures for agricultural irrigation in drought: 1) Operational measures will be taken at irrigation systems in critical condition. 2) In multi-purpose dams, the first priority will be given to drinking water, the second priority will be given to agricultural irrigation, and the operation plans will be made to generate energy with the rest. 3) The project called "1000 Ponds in 1000 Days" was initiated by the Ministry of Forestry and Water (Ministry of Agriculture and Forestry now) to reduce the impact of drought on irrigation.

Providing water only to fixed orchard, limited irrigation, alternative irrigation, not planting a second product, less water-consuming planting implemented by night irrigation were among further measures to be taken depending on the severity of the drought and on the basis of risk and crisis management. A commission was established for an even distribution of existing water, with the participation of Local Authorities, Local Managers, Irrigation Service Managers in case of critical situations. In the limited condition, a restricted water distribution program will be prepared by DSI and will be implemented by local administrators. In sufficient condition, water distribution will be ensured by supplying water in line with irrigation planning (MGM, 2014; p. 58). The Adana Governorship has met in April 2014 with the local state organizations including DSI to act on the water deficit (web8).

Event comparison in respect to drought hazard

The Standardized Precipitation Index (SPI) at various time scales was considered to determine meteorological droughts in the Seyhan River basin (Cavus, 2019; Cavus and Aksoy, 2019, 2020). The dry period was found 5-month long (at k = 1-month time scale), 23-month long (at k = 6-month time scale), and 59-month, almost 5-year, long (at k = 12-month time scale). Drought at the 12-month time scale lasted from January 1970 to November 1974 with extreme droughts spanning over the year 1973. Droughts were classified as severe [-1.51 in terms of SPI_1], extreme [-2.91 in terms of SPI_6], extreme [-2.78 in terms of SPI_{12}] (Cavus 2019; Cavus and Aksoy, 2019, 2020).

As for the second drought event, the dry period was found 7-month long (at k = 1-month time scale), 9-month long (at k = 6-month time scale), and 13-month long (at k = 12-month time scale). Drought at the 12-month time scale lasted from December 2013 to December 2014 with the most severe drought observed in May 2014. For the paired drought event in 2014, droughts were classified as mild/moderate [-1 in terms of SPI_1], extreme [-2.55 in terms of SPI_6], extreme [-2.34 in terms of SPI_{12}] (Cavus 2019; Cavus and Aksoy, 2019, 2020). It is seen that the drought in 1973 is more severe and much longer than the drought in 2014 when the calculated SPI values are considered (Figure 1).

Event comparison in respect to exposure

Adana is one of the most populated provinces in Turkey and the largest in the Seyhan River basin. Not only because of its size in terms of population but also due to its economical and agricultural importance, it is the main province in the basin. Adana, with the that time population of 1,035,377 (DPT, 2008; web3), was seriously exposed to drought in 1973 causing serious agricultural losses. Agricultural activities were disturbed (DMI, 1973). Farmers were not provided enough water for irrigation. Crop production has not been adequate in this period due to lack of water supply (web1). The energy sector was also negatively affected (DMI, 1973).

Precipitation records from 1960 to 2016 shows that the most severe drought was seen to extend over years 1972 with annual total precipitation 319.4 mm and 1973 with 407.9 mm in Adana meteorological station (long-term annual precipitation is 662.7 mm). With the annual total precipitation of 392 mm, 2013 has been the year with the third least precipitation of the 57-year observation period causing an extreme drought to extend over the year 2014 in Adana 41 years after the first drought in 1973 (web2). In 2014, population in the Adana province has increased to 2,165,595 (web4). Lacking water or shortage in the drinking water supply are more likely in case of a drought when increase in the urban area population is considered solely. Agricultural activities were disturbed as well as municipalities failed in supplying water to residential areas in 2014.

There are water-consuming and water using sectors in the river basin. Sectors that mostly consume water are agriculture (85%), domestic use (11%) and industry (4%). Water in the Seyhan River basin is also allocated for other water-using sectors such as environment and energy (ALFAR, 2017). Precautions to be taken by water-linked local bodies mainly for irrigation were discussed in "Agricultural Drought Crisis Center Meeting" organized by the Governorship of Adana in April 2014. Drought strategies and measures to be taken have been discussed in the meeting together with expectations from the Irrigation Unions to use water efficiently due to drought conditions (web8).

Event comparison in respect to vulnerability

A few more droughts were observed in this region in the period 1973-2014, but none has been as severe as the two paired drought events except one in the year 2007-2008 which had some consequences to accelerate the public institutions to take actions. Water level has fallen lower than its minimum in Catalan Dam providing water to the metropolitan area of Adana. As a solution, in cooperation with the Greater Municipality of the City of Adana, water was taken by pumps from a water level lower than the dead volume of the reservoir (Selek, 2019). Whenever a drought is observed, reduction in agricultural products, pastures and forest productions; depletion in water levels in the rivers, lakes and reservoirs become unavoidable. Also, increase in fires, losses in livestock and wild animals come out. These are all direct consequences of drought which cause, for example, a decrease in agricultural products that, in turn, results in a decrease in farmers' income; an increase in the food price (economical effects). Also, the rate of unemployment increases, tax revenues of the state decrease and finally migration starts (social effects). In order to avoid or minimize all these consequences, the Ministry of Food, Agriculture and Livestock (Ministry of Agriculture and Forestry now) subsidized 624,824 farmer families in 34 provinces by granting with cash support amounting 278,105,996 Turkish Liras (TL) in total (for drought in 2007) and 499,687 families in 35 provinces with 537,543,842 TL (for drought in 2008) (MGM, 2014, p.12) (1 USD = 1.1585 TL, 1 USD = 1.5207 TL, Exchange rates of Central Bank of Turkey as of 31/12/2007 and 31/12/2008, respectively). In the meantime, research studies on the drought have importantly been performed for which The Drought Assessment Report of Turkey was published by the

General Directorate of State Meteorological Works (MGM, 2014). This period of research has been devoted, by public authorities/institutions, mostly to the understanding of the drought.

There was less awareness compared to current conditions as drought is not considered as a natural disaster in Law number 7269 dated 15.05.1959 in Turkey (Sarican, 2015; p. 53-54). However, with 2010s, the awareness and perception have officially increased to prevent - when possible- or reduce -otherwise- negative impacts of drought. Different official documents were released at the public institutional level as the awareness is now at the governmental level (web9; Circular of Prime Ministry, 2017). Public institutions prepare drought management plans through projects such as Basin Protection Action Plan, Sectoral Water Allocation Plan and the Impact of Climate Change on Water Resources at basin-scale (SYGM, 2016; 2017; CYGM, 2016). Also, the 5-year Drought Action Plans (2013-2017) prepared for each of the 81 provinces in Turkey should be mentioned (Sarican, 2015). Another document is the 10th Development Plan (2014-2018) (Ministry of Development, 2013) that takes the drought into account and puts measures against its negative effects. Basin Protection Action Plans were performed by water-related public institutions in addition to studies performed by private companies for the purpose of using and allocating water efficiently among the sectors. It should importantly be emphasized that water quality has been given a priority in water resources management of river basins. Efforts specific to the Seyhan River basin for the above aims are summarized in the Impact of Climate Change on Water Resources Project and the Seyhan Basin Sectoral Water Allocation Plan accomplished by SYGM (2016) and SYGM (2017), and in the Seyhan Basin Pollution Prevention Action Plan by CYGM (2016). The Drought Management Plan of the Seyhan River basin has been prepared by the General Directorate of Water Management in 2020. It is important to emphasize that the drought has become a priority for water-related public authorities and for the General Directorate of Water Management in particular which is responsible for preparation of Basin Drought Action Plans released/prepared for 16 river basins (including the Seyhan River basin) out of 25 river basins in Turkey (web5).

In terms of preparedness, no basin-specific drought management plan was available in 1973. Instead, the drought crisis has been managed. However, no particular actions were obtained by the authors for the 1973 drought. There was still the lack of drought crisis management in 2014 against which following measures were foreseen for agricultural irrigation in drought (on the basis of risk and crisis management): A commission composed of Local Authorities, Local Managers, Irrigation Service Managers will evenly distribute existing water in case of critical conditions. Night irrigation will be provided with priority given to fixed facilities (orchards). When limited water is available, water distribution will be restricted through a program prepared by DSI and implemented by local administrators. When sufficient water is available, water will be distributed in line with irrigation planning (MGM, 2014; p. 58). The Governorship of Adana has met in April 2014 with the local water users to be better prepared for irrigation under drought conditions (web8).

On the other hand, there does not exists drought early warning system yet (Aras et al., 2019), which is within the future program of public organizations of the country.

Coping capacity was limited to a decision specific to the 1973 drought to aid/support farmers who were affected by the drought. No law or a similar legislative measure was available to cope with drought. In the 2014 drought, better coping capacity was observed in terms of legislation. Two laws exist to cope with the drought; one for subsidizing the loss of the farmers in case of drought when more than 40% loss occurs (Law number 2090, Year 1977); the second is about the agricultural insurance, TARSIM (Law number 5363, Year 2005).

No monetary data were obtained for the impacts of the paired droughts. However, loss in the cereal yield in 2014 could be informative. The average cereal yield is 570 kg ha^{-1} in 180,000 ha in Adana. In 2014, 26% less cereal was cropped, that is 269,100 tons less (Cetin, 2019).

When the intangible impacts of drought are concerned, it can be said that agricultural products, pastures and forest productions, water levels have all decreased while fires, mortality in cattle and wild animals have increased in 1973. No specific evidence for intangible impacts of the 2014 drought was reported. However, following general issues have been stressed in the Climate Change Strategy and Action Plan of Turkey (Ministry of Environment and Urbanization, no date).

Drought as a consequence of climate change is likely to affect poor people (farmers and women in particular) in their access to food and water, and in getting proper housing and health service. In the rural area, women are more active in agriculture; therefore, they are in danger more than men. Drought has clear social and economic effects (Ministry of Environment and Urbanization, no date; pp. 70-71). Droughts could make forest fires more frequent with longer duration in wider areas (Ministry of Environment and Urbanization, no date; p. 84). Climate change might bring tropical diseases for which clinics are in service in state hospitals of a number of cities (including Adana). Extreme temperature is a risk for skin cancer, particularly for those who work for the construction, agriculture, and tourism sectors as well as those who live at the coast.

Followings are expected economical, social and environmental impacts of drought in the Seyhan River basin:

Economical Impacts:
• Inadequate income resulting from declining agricultural production
• Decrease in industrial production due to water scarcity
• Economic loss in energy sector due to decline in energy production
• Unemployment due to decreased production
• Additional costs due to emergencies (e.g., water transfer, water and wastewater treatment costs, cost of campaigns to reduce water consumption

Social Impacts:
• Public health problems due to decrease in water and air quality
• Inequality due to the fact that economic impacts differ according to socio-economic groups (e.g., farmers suffer more than workers in the service sector)

Environmental Impacts:
• Decrease in quality of surface water and groundwater resources
• Damage to ecosystem, wetland and biodiversity (soil erosion, reduction of vegetation cover)
• Reduction in food and water resources
• Increase in frequency of forest fires spreading over larger areas
• Danger of salinity of soil and water resources

Summary

Drought has affected the population and the social life in the Mediterranean region of Turkey. People, as individuals or members of the society, irrigation unions, and also state authorities have reacted primarily by exploiting groundwater, building dams, infrastructure for water storage to provide water need mainly for agricultural irrigation. Consequently, hydrological regime has become highly artificial in this region. Of course, reservoirs have enabled economy to grow by providing water for agriculture which is a benefit at individual level as well as at the societal and public institutional levels. However, it should be mentioned that such anti-drought preventive actions have significant negative impacts causing depletion in lakes and drying of wetlands in the region due to the continuously increasing water supply from the reservoirs to use in irrigation systems. This can thus trigger the drought and reduction in water availability due to climatic and anthropogenic factors including reservoir operation and water management (Di Baldassarre et al., 2018).

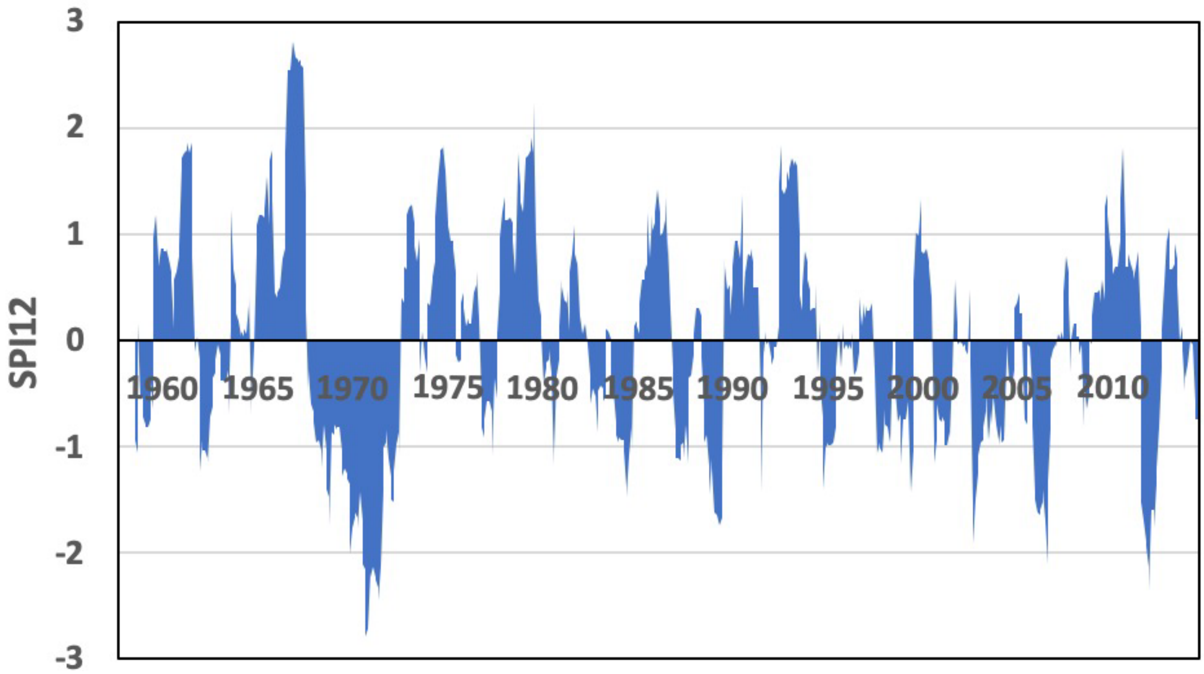

Figure 1: Dry and wet periods calculated from the SPI time series at k = 12-month time scale in Adana meteorological station

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ID 27

Paired flood events: 2007, 2010, and 2014 pluvial floods in Malmö city, Sweden

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Short description of both events with a focus on impacts

Malmö, the third largest city in Sweden, located on the southern coast, is frequently hit by flooding caused by heavy precipitation. In July 2007, central Malmö experienced flooding caused by a 50-year rainfall event after a long period of wet weather, which led to damaged buildings due to flooding of basements, and flooding of roads and railroads. The city was flooded again due to heavy precipitation in 2010 (25-year rainfall event) and in 2014, when a > 100-year rainfall event hit the area and exceeded the flooding in 2007 and 2010.

The flood events were to some extent similar, with widespread, pluvial flooding all over the city of Malmö. Areas along the main sewers were more affected than other areas, whereof areas with combined sewers were the most affected. However, the 2014 event was more severe, looking at the number of reported flooded properties (Sörensen & Mobini, 2017). The 2007 and 2010 resulted in >300 insurance claims and reports to the water utility company for damaged properties, respectively, while the 2014 event resulted in over 4700 insurance claims and reports (Sörensen & Mobini, 2017). The sum of the direct costs from the 2007, 2010, and 2014 event, has been estimated to at least SEK 1. 5 million (Sörensen and Mobini, 2017), SEK 60 million (GP, 2010), and 600 million, respectively (Grahn and Nyberg, 2017; SOU 2017:42). No casualties were reported for any of the events, but one fatality was reported from a neighbouring town in the 2007 event, and one person was in a critical situation during the 2014 event (Sörensen & Emilsson, 2019).

Descriptions of processes between events with a focus on risk management

One important factor for Malmö's vulnerability to pluvial flooding is the sewage system. Central Malmö has a mix of combined (40%), semi-separated (7%) and separate sewers (53%). The more densely populated areas have the combined system (sewage system where storm-water and sewage are drained with the same pipe), which leads to a higher risk of basement flooding (Sörensen, 2018). About 70% of the basement flooding during the 2014 rainfall event, occurred in houses with a combined sewage system (Hernebring et al., 2015), which shows that further improvements in the existing management network is needed.

Although Malmö experienced pluvial flooding in 2007 and 2010, it was not until after the severe pluvial flooding in 2011 in Copenhagen that the local water utility company, VA SYD raised concerns, and produced flood hazard maps over Malmö with precipitation data from the Copenhagen 2011 event as an extreme input. To the authors knowledge, no big changes were made in the management between the 2007, 2010 and 2014 events, apart from repair of damaged infrastructure after each event and ordinary work like separation of combined sewers and other capacity building infrastructure projects that were conducted as planned. Thus, no extraordinary flood prevention projects were done before the 2014 event, which came as a shock to most people in Malmö regardless of previous or nearby experience (Lindher, 2015).

After the 2014 event, the pluvial flood management planning has been strengthened and a person has been hired by the City of Malmö to work with the task. However, little extra money has been allocated for flood prevention and funds must be applied for internally in the municipality year by year. Lindher (2015) states that this is different from Copenhagen, where a large amount of money has been allocated for implementation of the pluvial flood management plan ('Skybrudsplan').

Event comparison in respect to pluvial flood hazard

Malmö was flooded in July 2007 after a heavy precipitation event where 89 mm fell between midnight and 19:45 in the evening on 5th of July (Figure 1) (Sörensen and Mobini, 2017). It had been raining for weeks before the event, with a rainfall amount between 5 and 15 mm per day during the week before the event, thus the ground was already saturated due to the recurring rainfall. This led to reduced infiltration capacity and a high groundwater table, leading to worse flooding than would normally be expected for a one-day rainfall (Sörensen and Mobini, 2017). All rainfall durations less than 4 hours represent less than a one in ten-year event, but for longer durations the return period was larger – between ten years and 50 years for eight days duration (Sörensen and Mobini, 2017). This rainfall event led to flooding of Malmö urban area, which is approximately 77 km^2. Several areas neighboring Malmö was also flooded, e.g. Lund and Helsingborg, but the largest rainfall was measured in Malmö.

In 2010 (14th of August), Malmö received high amounts of rain over the western and central areas, which caused flooding. The maximum rainfall measured in Malmö during the 2010 event was 60.8 mm in 6 hours, which corresponds to a 45 years return period. The average rainfall (50.9 mm in 6 hours) corresponds to 24 years return period in 2010, see figure 2 (Sörensen & Mobini, 2017). One pumping station (Spillepengen) was overloaded during the event, leading to flooding of some upstream areas, but the problem was resolved shortly after (Sörensen & Mobini, 2017).

Malmö experienced another severe flood in August 2014 following an extreme rainfall event. The rainfall event exceeded previously recorded records since rainfall monitoring started in the end of 1800s (Sörensen and Mobini 2017), with 100.1 mm during 24 hours, 36.1 mm during 1 hour and 17.5 mm during 15 minutes measured at the Swedish Meteorological and Hydrological Institute's (SMHI) station, Malmö A (SMHI, 2014). The maximum rainfall measured in Malmö during the 2014 event was 104.4 mm in 6 hours, which corresponds to a 300 years return period. The average (83.0 mm in 6 hours) corresponds to 135 years return period. Three of VA SYD's stations (Turbinen, Augustenborg and Bellevue) recorded even higher intensities (Figure 3). For durations longer than two hours, the rainfall event exceeds a 100-year rainfall (Figure 3) (Sörensen and Mobini 2017). A dozen rain gauges (tipping buckets) recorded the event. The largest total volume of rainfall of 122 mm during 6 hours was measured at Söderkulla by a temporary rain gauge, which corresponds to a return period of 400 years. The rainfall intensity varied greatly in both time and space between different parts of Malmö. It took approximately four days before all low-lying areas were drained from inundated water (Sörensen and Mobini, 2017).

The rainfall during the 2007 event was more evenly distributed over one week compared to the other two events, which had shorter durations and more distinct peaks of rainfall (Sörensen and Mobini, 2017). In comparison, the 2014 event was more intense than the 2007 and 2010 events for all durations less than 4 days, while the 2007 event was more intense for durations longer than 4 days (Sörensen and Mobini, 2017).

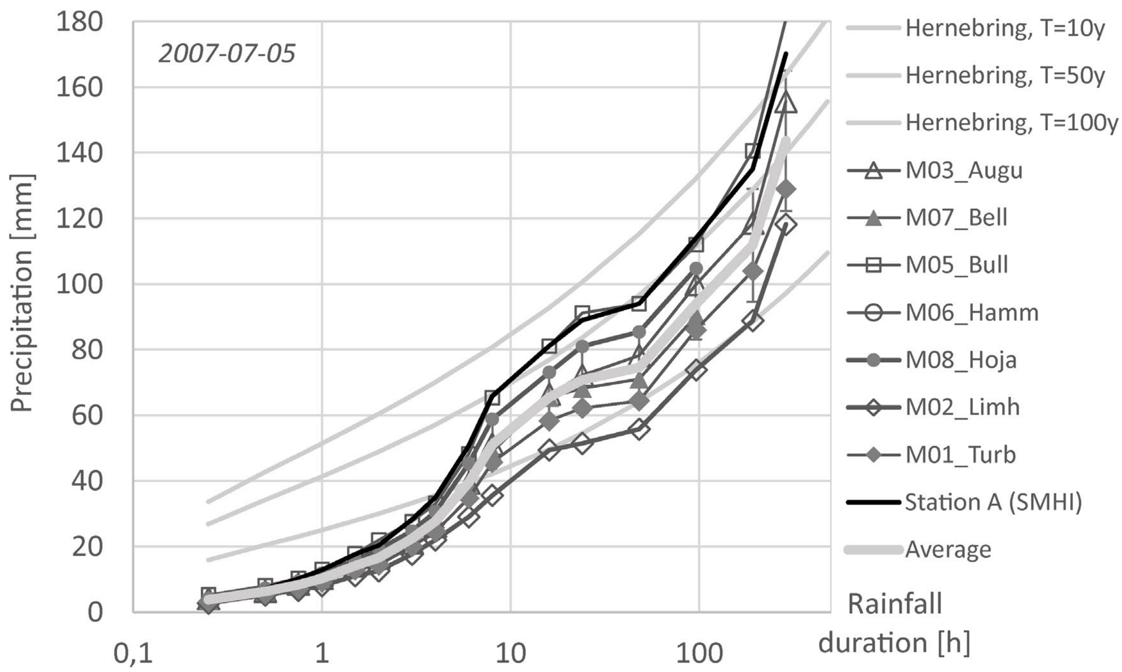

Figure 1. Rainfall volumes during and before the 2010 event in Malmö measured at eight rain gauges (From Sörensen & Mobini 2017).

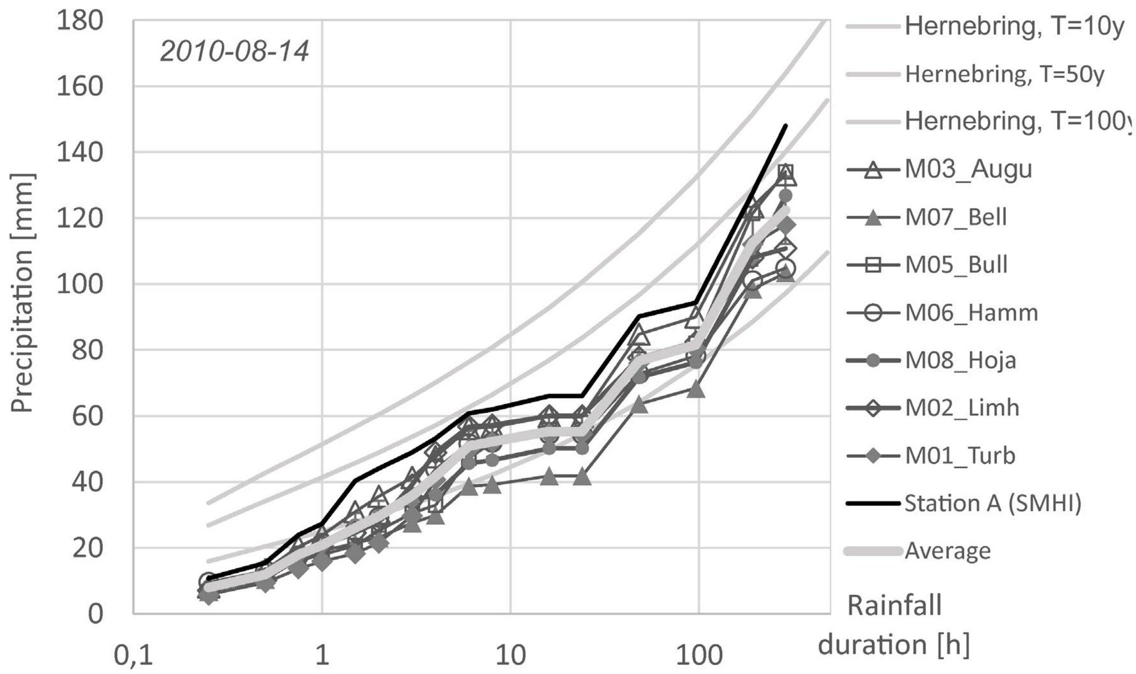

Figure 2. Rainfall volumes during and before the 2010 event in Malmö measured at eight rain gauges (From Sörensen & Mobini 2017).

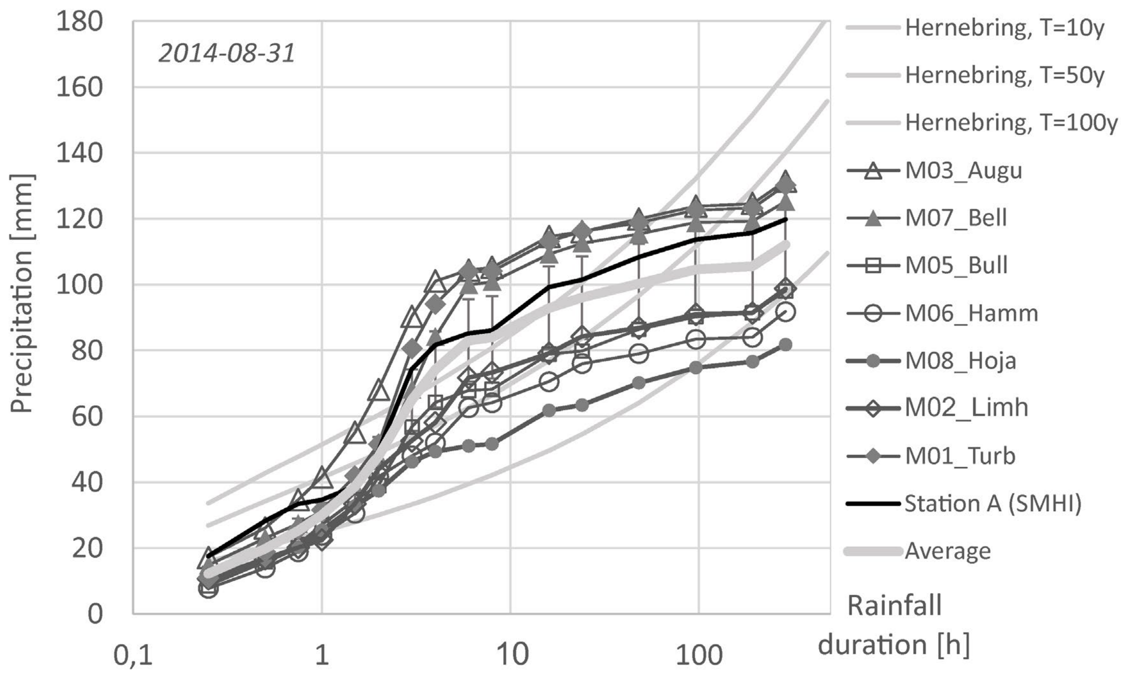

Figure 3. Rainfall volumes during and before the 2010 event in Malmö measured at nine rain gauges (From Sörensen & Mobini 2017).

Event comparison in respect to exposure

Malmö is the third largest city in Sweden. It's a coastal city located in a flat landscape, with the highest elevation at 37 m above sea level. The population has increased from 280,279 residents in 2007 to 317,375 residents in 2014 (Statistics Sweden, 2020). The population of Malmö city is expected to increase with another 50,000 by year 2029 (Malmö stad, 2020). For all the events, the areas along the main sewer pipes (<100m) were more flooded than other areas (figure 3 & 4). Areas with combined system were more flooded than other areas (figure 3 & 4) (Sörensen & Mobini, 2017). Since 2008–2010 a new, large area of Malmö, called Hyllie, is developing. It is not known what impact this new area had on the sewer system during the 2014 event. The city is also continuously being densified.

In terms of impact, over 20 roads were closed off due to flooding during the 2007 event, which resulted in traffic congestion all over the city, and people were advised to not drive into central areas in Malmö. A railway tunnel was also flooded (FOI, 2009). One casualty was reported in a neighboring city, Helsingborg, due to a flooded car. The manual control of a floodgate in Toftanäs (eastern Malmö) was covered with water, which led the open retention basin not being drained. Consequently, many buildings in the surrounding area were flooded (Sörensen and Mobini, 2017). A pumping station in Segevång was overloaded and stopped working during the rainfall event, which led to flooding of properties in the area and consequent claims for around 1.5 million SEK (Sörensen and Mobini, 2017). A large number of claims were made due to basement flooding in buildings, which was caused partly by water from floor drains connected to the sewage system, and from overland flow (up to 320 claims from two of the largest insurance companies in the region). Approximately 50% of all the basement flooding was due to groundwater intrusion through the foundation walls because of long-lasting rainfall (Sörensen and Mobini, 2017).

The flood extent in 2010 was smaller than the 2007 flood, but resulted in similar number of flood claims. Multiple properties had their basements flooded, according to the flood claims. Large interruptions in traffic occurred and some cars got stuck in the water masses. The flood caused damages amounting up to SEK 60 million (GP, 2010). The flooding in 2014 resulted in large damages to properties and disruptions in societal functions totally up to SEK 600 million (Stadsbyggnad, 2016). In the morning of the 31st of August (05:48-9:52) the emergency rescue services received 219 calls from affected people. There were large issues with viaducts, where the water reached the car roofs and people had to swim from their vehicles. Floating cars were consequently inspected by the police. Roads were shut down and city bus traffic was canceled after several buses crashed. Trains were canceled, and many residents experienced power cuts (up to 3000 customers). During the 2014 events, the main hospital and a high-rise building called Kronprinsen were severely flooded (Sörensen & Mobini, 2017). The wastewater treatment plants were forced to discharge uncontaminated wastewater, and therefore the public was advised against swimming in the sea (Nyberg et al., 2019). However, no injuries were reported during the event. The event resulted in over 260 million SEK, claimed from affected residents. The local insurance companies received around 5,800 claims regarding housing (4,270 claims), business (450), and cars (820) (Sydsvenskan, 2014). Many had to leave their homes because of extensive water damage and could not return until more than a year later (Stadsbyggnad, 2016). Over 3,000 vehicles were estimated to have been affected by the flooding. VA SYD's (regional water utility company) facilities were damaged at a value of about 3 million (Gustavsson and Lundström, 2015).

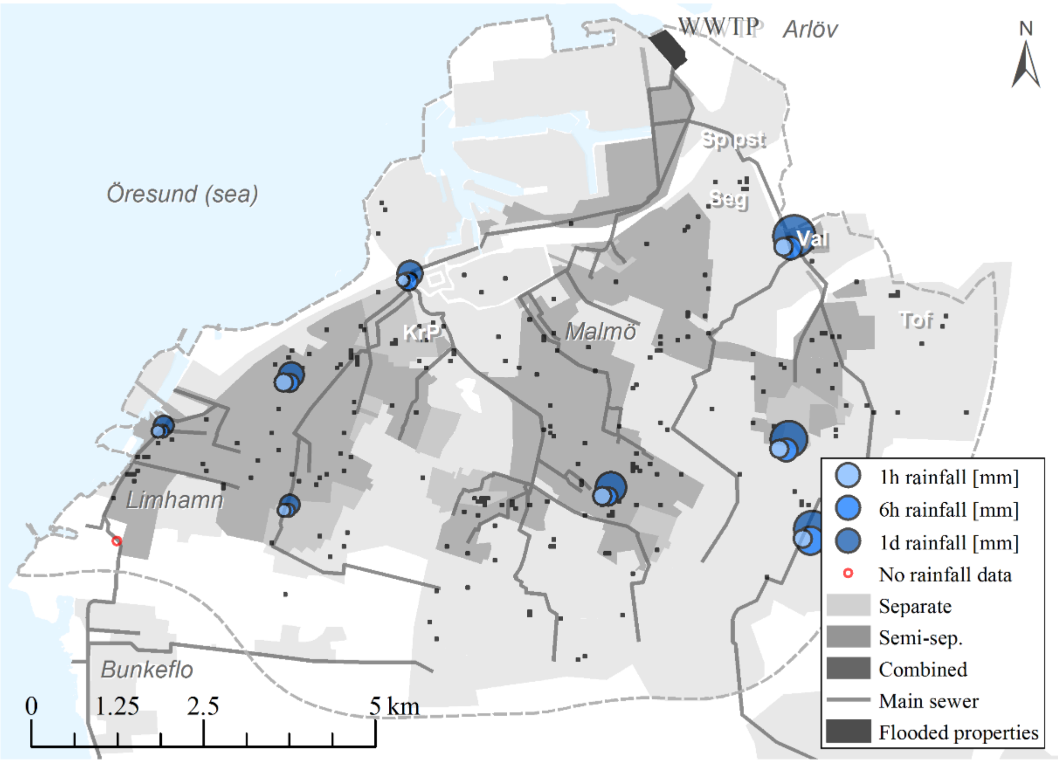

Figure 4. Flood event 2007, Malmö. Cells where flooding was reported are marked with black dots. Rainfall volume for 1h (light blue circles), rainfall volume for 6h (mid-blue circles) and rainfall volume for 1d (dark blue circles), where a larger circle represents bigger rainfall volume. The largest size of each circle represents the largest rainfall volume in the data set for the corresponding duration and the smallest size represent the smallest rainfall volume. (From Sörensen & Mobini 2017).

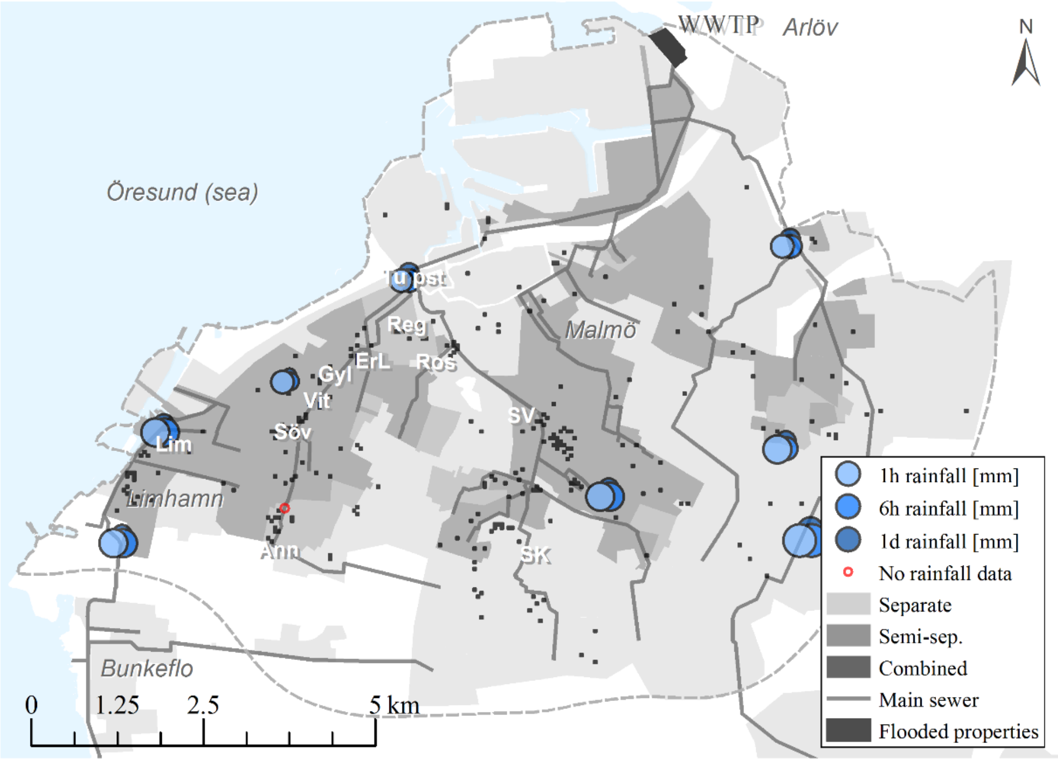

Figure 5. Flood event 2010, Malmö. Cells where flooding was reported are marked with black dots. Rainfall volume for 1h (light blue circles), rainfall volume for 6h (mid-blue circles) and rainfall volume for 1d (dark blue circles), where a larger circle represents bigger rainfall volume. The largest size of each circle represents the largest rainfall volume in the data set for the corresponding duration and the smallest size represent the smallest rainfall volume. (From Sörensen & Mobini 2017).

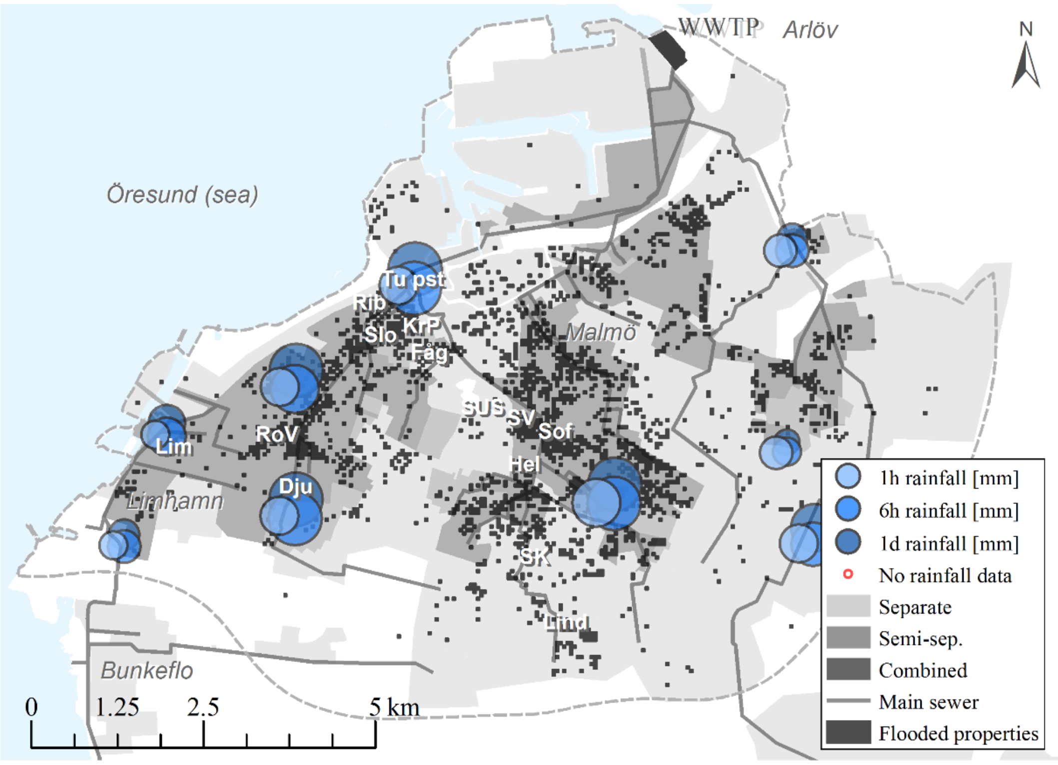

Figure 6. Flood event 2014, Malmö. Cells where flooding was reported are marked with black dots. Rainfall volume for 1h (light blue circles), rainfall volume for 6h (mid-blue circles) and

rainfall volume for 1d (dark blue circles), where a larger circle represents bigger rainfall volume. The largest size of each circle represents the largest rainfall volume in the data set for the corresponding duration and the smallest size represent the smallest rainfall volume. (From Sörensen & Mobini 2017).

Event comparison in respect to vulnerability

In regard to early warning systems, SMHI is responsible for the weather related national early warning system. Forecast data prior to the 2014 event showed precipitation amounts of the same order of magnitude as the resulting rainfall event, but not the exact location. As the warning system is not adapted for smaller, limited areas – no warnings were given (Hernebring et al., 2015), and there was no risk communication to the general public (Bentzel, 2019). However, as the event unfolded, SMHI issued class 1 warnings and advices were issued. Class 1 warnings of heavy rains represent "heavy rain with more than 35 mm within 12 hours up to 70 mm within 24 hours, with risk of large puddles, overflowing drains and flooded cellars" (SMHI, 2020). Class 1 warning is used when "weather is expected that involves certain risks to the public and disruptions to some social functions" and is the lowest warning level of three from SMHI.

The timing of the precipitation events could potentially play a role in people's awareness and preparedness for the floods. The 2007 event occurred after a week of wet weather, and the 2010 event unfolded during the day, while the heavy precipitation event in 2014 occurred early in the morning, leaving many people surprised and unprepared for the event.

In Sweden, flood damage to residential property is covered by basic home insurance, and is not connected to an actual flood risk in a specific area. The insurance covers damage to buildings and moveable property when the flood is caused by rain of an intensity of 1 mm per minute or 50 mm per day, by snowmelt, or by increasing lake levels. The water must have entered the building via surface runoff through valves, windows or door openings, or through the sewage system. The insurance coverage amongst homeowners in Sweden is often assumed to be close to 100% (Grahn and Nyberg, 2017). According to Insurance Sweden, the coverage is 96,7%. The coverage is however lower in the group 'born outside Sweden' (89,2%), where coverage in the group 'born outside Europe' is even lower (86,1%) (Insurance Sweden, 2019). Also young people have a lower coverage than on average (age 16–24: 94%, age 25–35: 92%) (SVT, 2015).

There is a strong need for more information and advice to real estate managers, house owners and local housing organisations (Lindher, 2015). The preparedness is mostly focused on the City of Malmö, which has an established collaboration with the utility company (Lindher, 2015). Lindher also reports that the collaboration between different departments were good during the 2014 event, but that they wanted better warnings, that the staff were not mentally prepared, that their roles and responsibilities were unclear, that a central coordinator would have been good and that there was a need for an interactive map with information. Directions and guidance for municipalities on how to mitigate urban flood risk are lacking from national authorities in Sweden (Becker 2018). No similar study has been found for the 2007 and 2010 events.

Summary

The general development regarding pluvial flood risk management in Malmö is driven by good knowledge about climate change (Wihlborg et al., 2019) and strong interest in stormwater management since the days of Peter Stahre, who was a front-runner in Malmö in the field of sustainable solutions to stormwater management (Stahre, 2006). Both water professionals, urban planners, and ecologists think that ecosystem services are important drivers for implementation of more blue-green infrastructure, often with focus on flood protection (Wihlborg et al., 2019). Despite recent flood events in 2007 and 2010, as well as knowledge about the extreme flood event in the neighboring city of Copenhagen in 2011, the extreme event in 2014 came as a chock to many in the staff and the general public.

The 2007 rainfall event was more evenly distributed over the duration of one week, while the 2014 event had a more distinct peak of rainfall and was more intense for durations shorter than four days. However, for durations longer than four days, the 2007 event was more intense (Sörensen and Mobini, 2017). The 2014 event produced larger impacts than the 2007 event. For example, during the 2007 event, areas within 100 m from the main (sewage) system were more than twice as affected by flooding (based on number of flood claims) compared to areas further away. For the 2010 and the 2014 event, areas close to the main system were four times affected by flooding (based on number of flood claims), while the ratio was only two times for the 2007. This indicates that the soil moisture affects the hydrological response during large rainfall events, leading to flooding further away from the main sewers, which is of importance to drainage design. For very intense rainfall events, like the 2010 and 2014 events, more properties near the main sewers where flooded due to the rapid response of the sewer system.

For Malmö, the higher intensity of the 2014 rainfall event, compared to the 2007 and 2010 events, led to larger impacts on the society. The intensity of heavy summer rains in Sweden is expected to increase by 10–15% between the period 1961–1990 and the period 2071–2100 (Grahn and Nyberg, 2017). Thus, hazardous events such as the Malmö 2014 event are expected to occur more frequently in the future. Following the 2014 event, City of Malmö has together with VA SYD (regional wastewater organization) developed a flood management plan – a long-term plan for how the city should be equipped to meet extreme rainfall. For example, in 2045, Malmö should be able to cope with a 100-year rainfall event. The plan was approved by the Technical Committee in Malmö in 2017, and was supplemented in 2018 by an action plan for reconstructions (VA SYD, 2019). The idea is to work on three perspectives in parallel (Malmberg, 2018): 1) construction projects where flood risk reduction is the main aim; 2) inclusion of flood risk reduction in other projects; and 3) information campaign to engage private property owners in flood risk reduction. All three are focused on risk reduction from the hazard perspective (water management), rather than on vulnerability or exposure. All actions in the plan are finances year by year, through internal application for funding within the municipality (Malmö stad, 2018). Interestingly, while the flood management plan claims that already existing green spaces should be protected, it does not emphasise implementation of more blue-green infrastructure, despite that blue-green infrastructure lower the flood risk by a factor of 10 in comparison with areas with combined sewers (Sörensen & Emilsson, 2019). The study was done in a famous blue-green area of Malmö, Augustenborg, but it was published after the plan was approved.

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ID 28

Paired pluvial flood events: 2010 and 2016 pluvial floods in Ho Chi Minh City in Vietnam

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Short description of both events with a focus on impacts

In recent years, Ho Chi Minh City (HCMC) has been coping with flooding situations due to the increase of heavy rainfall events of the 2- to 3-hour durations during rainy seasons (from May to November) (Viet, 2008; Lempert et al., 2013; Ho et al., 2014). The rainfall amount of these extreme events is getting exceeded the drainage capacity of the urban storm sewer system, that caused causes several deeply flooded locations, according to annual reports of SCFC (Steering Center for Urban Flood Control Program in HCMC). As a result, daily living activities of inhabitants as well as their properties and public works are severely affected in the direct or indirect ways in rainy seasons (ADB, 2010; Jha et al., 2012). It costs the city more US$ 65 Million in the expected annual damage due to flooding (FIM, 2013). In this study, paired pluvial floods were the extreme ones in the year 2010 and 2016, these total extreme rainfall amounts were 95.0 mm (on 28/08/2010) and 159.6 mm (on 26/08/2016). After the 3-hour duration in the 2010 event, 50 flood locations on streets were inundated with the flood depth of 0.1 ÷ 0.5 m, and the total flooded surface area of 105,940 m^2 in an estimated way (SCFC, 2011). While in the 2016 event, it was reported that 31 points on streets were affected with the flood depth from 0.1 m to 0.4 m, and the total flooded surface area of 75,330 m^2 (SCFC, 2016). Especially, the landing zone at the International Tan Son Nhat (TSN) Airport was inundated with 0.3 m in depth that caused the turbulent situation in the airport. Particularly, 18 flights to TSN were rescheduled to land at other nearby airports while those 50 flights planned to depart from the HCMC airdrome were forced to delay or cancel due to the heavy downpour[1]. Following this, the direct economic impacts of the 2016 event were approximately US $0.49 million, greater US $0.17 million than the 2010 event due to adding reported insurance cost of the damaged vehicle[2]. Besides, the heavy rainfall events usually occur in the rush hour (16:00 – 20:00), thus the traffic could be got stuck and vehicles are seriously damaged as the below figure[3]. Additionally, the real estate prices at several previous hotspots were growing due to flooding reduction compared with the year 2010 and the year 2016 (Chung et al., 2018).

[1] The number of affected flights were statistic from Tuoi Tre Online News, https://tuoitre.vn/cuc-hang-khong-bao-nhieu-bai-do-o-tan-son-nhat-ngap-trong-mua-1161784.htm

[2] The level of evidences of direct economic impacts are newspaper articles and expert judgement in Vietnamese.

[3] https://tuoitre.vn/sai-gon-chieu-cuoi-tuan-mua-tam-ta-ket-xe-nhieu-noi-1161490.htm

a. The 2010 event *b. The 2016 event, at TSN airport*

Figure 1. The deeply flooded hotspots after the extreme events. (Source: Internet)

Descriptions of processes between events with a focus on risk management

The urban drainage systems in HCMC were installed over fifty years ago and located mainly in the downtown but they developed slower than urbanization. That has resulted in overloaded capacity in the existing drainage systems due to the increasing rainfall intensity (ADB, 2010; Tu & Nitivattananon, 2011). Since 2001, the master plan of the HCMC urban drainage systems (PM, 2001) was implemented with several ODA (Official Development Assistance) projects to upgrade and renovate these networks for inundation prevention. As a result, until 2010, a half of over 100 flooded points were prevented and reduced in respect to depth, area and time of flooding. However, there have emerged some new points in the suburban districts because of river encroachment and outlet congestion under residential activities (HCMPC, 2019). Besides, the slow progress and the weak construction organization of drainage infrastructure projects also affected the drainage capacity of the systems (Ho, 2008). After six years, these flooding prevention works have been operating effectively (Anh, 2017) in mitigating inundation conditions in HCMC. Particularly, about 40 main routes in 2016 were flooded by extreme rainfall events causing exceeding the drainage capacity of HCMC new designed stormwater system (Rujner & Goedecke, 2016). HCMC was aware of and prepared for the risk management aspects of pluvial flood by multi-stakeholder involvements in urban drainage system management in the early 2010s (Anh, 2017). Moreover, the city authorities developed capacity building activities base on the HCMC Flood and Inundation Management project (FIM, 2013) in the mid-2010s.

Event comparison in respect to pluvial flood hazard

According to The National Centre for Hydro-Meteorological Forecasting (NCHMF, website: nchmf.gov.vn), rainfall characteristics of HCMC are scattered showers and thunderstorms in the evening. The annual number of rainfall events in HCMC is reported by Southern Regional Hydro-meteorological Center, and a rainfall event is described as the sum of the accumulated rainfall within a short duration below 24 hours (Nguyen et al., 1998). In this section, the comparison of characteristics of rainfall events between the year 2010 and the year 2016 is shown in **Table 1**. In the first comparison, the total number of rainfall events in 2016 was 135, nearly 20% smaller than in 2010 with 168 events. According to SCFC observations, a rainfall event, with a rainfall amount exceeding 30 mm, is capable of causing local flooding situations on roads in HCMC. Thereafter, the number of rainfall events causing flooding in 2016 was 47, obtained 34.8% of the total number; meanwhile, that number in 2010 was 82 (48.8%). Consequently, the number of rainfall events causing flooding in 2016 had a decrease of approximately 43% compared to the equivalent value in 2010 due to upgrading more efficiently the urban drainage system from ODA projects (e.g the Nhieu Loc – Thi Nghe canal sanitation project (2003 – 2012)[4] , the Tan Hoa – Lo Gom canal upgrading project (2011 – 2015)[5]. Particularly, the 95.0-mm storm event in 3 hours on 28/8/2010 with the 3-year return period (Viet, 2008) resulted in about 105,940-m^2 flooded surface area on streets with the flood depth of 0.1 ÷ 0.5 m, and dozens of motorcycles in estimate were stalled (SCFC, 2011). In comparison, the 159.6-mm one in 3 hours on 26/8/2016 with the 30-year return period (Viet, 2008), 68% higher than the former (SCFC, 2016). This event affected nearly 75,330-m^2 surface area flooding on streets corresponding to the flood depth from 0.1 m to 0.4 m, then about hundreds of cars and motorcycles stalled due to flooded engines (SCFC, 2016). In the fact that, the amount of these two rainfall events exceeded the drainage capacity of the urban drainage system with the 85.36-mm rainfall amount over 3 hours (PM, 2001). It was a convincing argument that the 28.9% decrease of flooded street areas between the year 2010 and 2016 resulted from stormwater network upgrading for HCMC flooding control.

Table 1. The comparison of rainfall characteristics between Year 2010 and Year 2016

No.	Description	Year 2010	Year 2016	Up/Down (+/-)
1	Total number of rainfall events	168	135	- 19.6%
2	Number of rainfall events causing flooding	82	47	-42.7%
3	Ratio of Row 2 to Row 1 (%)	48.8	34.8	
4	The rainfall amount of the extreme event (mm)	95.0 on Aug. 28	159.6 on Aug. 26	68.0%

Event comparison in respect to exposure

After the short duration in the 2010 event, 50 flood points on streets were inundated with the flood depth of 0.1 ÷ 0.5 m and the road surface area of 105,940 m^2 (SCFC, 2011); meanwhile, it was obtained with the flood points of 31 hotspots on streets, affected with the flood depth from 0.1 m to 0.4 m and the road surface area of 75,330 m^2 (SCFC, 2016). Especially, the landing zone at the International Tan Son Nhat Airport, the most important aviation gateway to Vietnam, was inundated with 0.3 m in depth that caused the turbulent situation in the airport. Nearly 70 flights of three main airlines operating at TSN had to delay and cancel flighting schedules, and even switch to touch down at other surrounding domestic/international airports due to the heavy storm. According to population density calculating at the statistical yearbooks of HCMC in 2010 and 2016, also depth-damage curves in the HCMC Flood & Inundation Management Final Report (FIM, 2013), the estimated number of people exposed were obtained respectively 10,840 and 12,369 people due to these extreme rainfall events with the max flood depth of 0.5 m.

Event comparison in respect to vulnerability

Since 2010, before the annual rainy season, the Steering Committee for Flood Prevention and People Rescue, directly under the Ho Chi Minh City People's Committee, has been ready to

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[4] http://www.thanhniennews.com/society/the-resurrection-of-nhieu-locthi-nghe-how-hcmc-brought-the-black-water-canal-back-from-the-dead-30431.html

[5] https://tuoitrenews.vn/features/27137/revived-canal-benefits-residents-improves-ho-chi-minh-city

coordinate activities of all multi-stakeholders to strengthen the prevention of disasters and search-and-find rescue mission (SCFC, 2011, 2016; Anh, 2017). To minimize flood risk in the city, only structural measures in 2010, i.e., mobile pumping station, was used for coping capacity with inundation in the city (SCFC, 2011). But in 2016, green infrastructure approaches and sluice gate operations were applied in the integrated flood management strategy of HCMC in an effective way (Jha et al., 2012; SCFC, 2016). In addition, the preparedness and organizational emergency management showed significant results in 2016 after implementing the decision on the detailed plan for flood control in the short term 2011 – 2015 (HCMPC, 2012). Particularly, dredging the stormwater network and forecasting flood hazards were actions for preparedness in the early 2010s (SCFC, 2011), then new more measures were approached such as announcing flood hotspots on radio channels and integrating flood hazard maps with Google Map (SCFC, 2016). Propaganda activities for flood awareness and precaution are implemented on social media, flyers, training courses to the community (HCMPC, 2010, 2016).

Summary

Due to climate change, rainfall intensity in HCMC has been increasing that resulting in exceeded discharge in the storm sewer network, however, flood integrated management projects supported by ODA were executed in order to reduce inundation risk. As a result, flood positions in the 2016 rainfall events were smaller than in the 2010 one due to the effective operation of these projects. On the other hand, there is a lack of statistical information in flood damage assessment after each extreme rainfall event in the city. Therefore, it is still rather limited and uncertain to fully quantify the exposure, vulnerability and impacts of these two rainfall events as well as to assess the effectiveness of integrated flood mitigation programs in HCMC.

Acknowledgements

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ID 29

Paired flood events: Selly Park, Birmingham (UK), Paired Riverine and Pluvial Flood Events: 2008, 2016, 2018

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Acknowledgements: this case study contains data from the UK Met Office, UK National River Flow Archive (NRFA), and data and images from the Selly Park South Neighbourhood Association

Catchment background and introduction

Birmingham, the second largest city in the United Kingdom, is situated in the Upper Tame catchment, West Midlands. The Tame, a tributary of the River Trent, has the most heavily urbanised catchment for its size in the UK (42% urban) (Lawler et al., 2006) with hydrological impacts that include increased runoff (both quantity and celerity) from impermeable surfaces (Webster et al., 2001). It has also been suggested that more properties in Birmingham are at risk of surface water flooding than anywhere else in the UK with the exception of London (BCC, 2015). This reflects the density of urban development in the catchment that enables precipitation to be routed rapidly via the drainage infrastructure to local rivers and streams. The problem is compounded further by historic developments in the floodplain, and local river channelization and straightening which increase the impact of local flood events (BCC, 2015).

Birmingham has experienced a number of localised flooding events in the last twenty years: 14 recorded floods from March 1998 to March 2008 (Kotecha, 2008; BCC, 2017); and 13 from April 2008 to February 2020 (BCC, 2017; BCC, 2018), with recent flooding in September and November 2019 (BirminghamLive, 2019a; BirminghamLive, 2019b). The most severe flood events occurred in September 2008, June 2016, and May 2018 which resulted in several internal property flooding incidents across the city (BCC, 2018). All three events occurred as a result of intense convective rainstorms and largely impacted the Selly Park area of Birmingham, a residential neighbourhood situated 3km to the South of the city centre. Flooding arises through a combination of riverine (fluvial) flooding from the Bourn Brook and River Rea, surface water (pluvial), and sewer flooding (BCC, 2018; Birmingham Post, 2018).

Due to the nature of riverine flooding and its management in Selly Park, the area is often divided into Selly Park North and Selly Park South for descriptive purposes. Selly Park North experiences flooding from both the Bourn Brook and River Rea watercourses, the confluence of which lies immediately downstream of Selly Park North (**Figure 1**), as well as surface water and sewer flooding. Selly Park South experiences flooding from the River Rea watercourse (**Figure 2**), surface water and sewer flooding. The Bourn Brook watercourse, an east flowing tributary of the Rea, has an area of #

~28.1km and a 1 in 100-year (1% Annual Exceedance Probability; AEP) flow rate of 21.7m^3/s (NRFA dataset) (BCC, 2012). Water quality dynamics in the Bourn Brook have been intensively studied (e.g. Khamis et al., 2018) with the upper reaches relatively natural (as the streams flow through a country park). The River Rea catchment has an area of ~87km^2 and a 1 in 100-year (1% AEP) flow rate of 53.68m^3/s (NFRA dataset), joining the

River Tame north of Birmingham (BCC, 2012). In common with the rest of the Tame catchment, the Rea catchment and Selly Park area are highly urbanised with 45% urbanisation recorded at the main gauge on the River Rea (Calthorpe Park) (NRFA, n.d.). Dense urbanisation primarily occurs at the confluence of the Bourn Brook and River Rea, which has contributed to Selly Park having an estimated 10% chance of flooding (1 in 50 years), which is the highest category for very significant flood risk (Environment Agency, 2018). Further, the Bourn Brook has no Environment Agency nor Local Authority gauges or monitoring.

Figure 1: Route of flooding in Selly Park North from the Bourn Brook and River Rea

Figure 2: Selly Park South flood area from the River Rea

Short description of both events with a focus on impacts

Selly Park, Birmingham, has experienced three severe flood events in the past 12 years: 6th September 2008, 16th June 2016 (which followed two earlier events on June 8th and 10th), and 27th May 2018 (BCC, 2017; BCC, 2018). All three events were caused by intense convective and localised rainfall (Met Office, 2008; BCC, 2016; Environment Agency, 2018). Riverine (fluvial) flooding occurred from the Bourn Brook and River Rea, with additional surface-water (pluvial) and sewer flooding affecting both Selly Park North and Selly Park South (BCC, 2018; Birmingham Post, 2018). No events resulted in any fatalities in Selly Park.

In Selly Park North, flooding occurs as the Bourn Brook exceeds the channel capacity, which is reduced by road-bridge infrastructure (Pershore Road) near the confluence of the Bourn Brook and the River Rea. As the flow of the Bourn Brook increases, floodwaters are increasingly impeded by the bridge resulting in the inundation of one of the main arterial roads into Birmingham and residential areas of Sir John's Road, Fourth Avenue and a lower area of Third Avenue (Rea Catchment Partnership, N.D.a). The configuration of street architecture, and the limited space between the terraced houses, also strongly influences and constrains flow. In Selly Park South, flooding occurs from the River Rea upstream of Dogpool Bridge (Rea Catchment Partnership, N.D.b), again due to the constriction of floodwater flows by bridge infrastructure. Subsequent floodwaters inundate Dogpool Lane and the residential areas of Fashoda Road, Cecil Road, Hobson Road and Kitchener Road (Rea Catchment Partnership, N.D.b; BCC, 2012).

2008 Flooding

Although there is limited information available on the impacts of the 2008 flooding in Selly Park, around 70-100 properties are reported to have been inundated across the city (Environment Agency, 2018). Birmingham City Council, however, confirm a large proportion of these occurred in Selly Park (42 properties experiencing internal flooding) (BCC, 2011; 2012). 25 properties were internally inundated in the residential area of Selly Park South (BCC, 2012). Dogpool Lane was closed due to dangerously high river levels (**Figure 3**), leading to traffic delays and diversions through other flooded roads that caused the movement of floodwaters into properties (bow waves) and ultimately further road closures. In Selly Park North, 17 properties experienced internal flooding in the residential areas (BCC, 2012). The emergency services were called to rescue stranded individuals from flooded properties in areas surrounding the Bourn Brook (BirminghamLive, 2008). The resulting property flood damages also required ~80 people to move out of their properties, in some cases up to 6 months.

Figure 3: Dogpool Bridge reaching capacity from high River Rea flows in 2008, that results in flooding in Selly Park South. Photo published with permission from the Selly Park South Neighbourhood Association (SPSNF, n.d.)

2016 Flooding

Flooding in 2016 inundated the same areas of Selly Park North and South as 2008, largely due to flow constriction by bridge infrastructure (BCC, 2016). However, the 2016 event was larger than the 2008 event and resulted in >100 flooded properties (primarily in Selly Park North) (BCC, 2016; Environment Agency & RCP, 2016; BBC News, 2016; BBC News, 2018). In Selly Park North, while there was localised surface-water flooding, 33 residential properties flooded internally due to riverine flooding from the Bourn Brook (BCC, 2016; Environment Agency, 2018). A further two properties were flooded from surface-water draining from Eastern Road playing fields (BCC, 2016). Properties and roads (Dogpool Lane and residential streets) in Selly Park South were also flooded (SPSNF, 2016). The exact number of properties internally flooded Selly Park South by riverine and surface-water flooding is not known. However, the flood impacts were described as not as severe as 2008 by the local Neighbourhood Forum (SPSNF, 2016).

2018 Flooding

During the 2018 flood event that impacted Selly Park, similar river levels to previous events occurred. However, the new Selly Park South flood alleviation scheme (constructed following the 2016 flood event and which became operational immediately prior to the 2018 flood event) successfully protected properties against riverine flooding from the River Rea (EA, 2018). A small number of properties were affected by surface-water flooding from overwhelmed drainage systems and bow waves from vehicles travelling through floodwater (BCC, 2018). While the Selly Park South alleviation scheme worked effectively, 150 properties were either directly or indirectly impacted by flooding in Selly Park North (**Figure 4**) from the River Rea, the Bourn Brook and surface-water due to delays with the Selly Park North flood alleviation scheme (SPNFAG, 2018). However, reports by Birmingham City Council indicate 29 properties were internally flooded, with 1 additional properties flooded by surface-water (BCC, 2018). Residential roads were flooded up to depths of 1m that caused cars to be submerged (BBC News, 2018b).

Figure 4: High floodwater levels in Sir John's Road, Selly Park North in 2018 (floodwaters from the Bourn Brook) after previously being flooded in 2016. Photo published with permission from BBC News at bbc.co.uk/news (BBC News, 2018)

Descriptions of processes between events with a focus on risk management

In the UK, street drainage is the responsibility of the City Council, while the drainage (and sewage) infrastructure is the responsibility of the local water utility (in this case Severn Trent), and responsibility for the 'main stem' rivers (the Rea and the Bourn Brook) lies with the Environment Agency. The Council has responsibility to co-ordinate between organisations, with the Environment Agency taking the lead on flood warning and protection (as recommended by the 'Pitt Review' following national flooding in 2007).

Before the 2008 event, a Regional Flood Risk Appraisal was completed in 2007 (BCC, 2012). However, no significant management or protection was in place during the flood event due to no severe floods occurring in the Selly Park area since 1928. Following the 2008 flooding, a hydrological / hydraulic model of the catchment was commissioned by the Environment Agency that highlighted the importance of local topography. Sewer flows were modelled separately. Flood warning systems were also improved (BCC, 2012). Following the requirements of the 2009 Flood Risk Regulations (legislation that implements the 2007 EU Floods Directive in the UK to produce preliminary flood risk assessments, identify flood risk areas, prepare flood hazard and risk maps, and implement flood risk management plans), a Level 1 Strategic Flood Risk Assessment was completed in 2010 (BCC, 2012). This was updated with a Preliminary Food Risk Assessment in 2011 (BCC, 2011) and Level 1 and Level 2 Strategic Flood Risk Assessments in 2012 in accordance with Planning Policy Statement 25 (PPS25) (comprising elements of the UK's flood risk management policy that encourages planning of development to reduce and avoid flood risk) (BCC, 2012; BCC, 2012b; Department for Communities and Local Government, 2009). This included mitigation strategies for Selly Park flood zones (1 in 100-year/1% AEP and 1 in 1000-year/0.1% AEP flood zones from the River Rea and Bourn Brook) including implementing raised defences (protection standards of 1 in 50-year flood events/2% AEP), flood warning services and their dissemination methods for the River Rea (882 properties covered by flood warning services), and emergency response planning (BCC, 2012).

The Strategic Assessment also included recommendations for sustainable urban drainage systems (SUDS), further development control, emergency planning, and development of a Surface Water Plan (BCC, 2012). The latter was finalised in 2015 (BCC, 2015). The measures for Selly Park included flood storage, further raised flood defences, sewer inspection and maintenance with increased culvert capacity, and model improvements for future alleviation schemes (BCC, 2015). Resilience was also improved through increased awareness through public engagement and flood risk information sharing with the wider community (websites, flood fairs, action groups and leaflets) (BCC, 2015). In 2012, the Selly Park South Dogpool Lane Bridge that constricted flows during the 2008 flood, particularly reinforcement blocks to accommodate the weight of traffic that acted as a blockage and was suggested to have increased the severity of the flooding in surrounding roads, was replaced (**Figure 5**) (Clayton, 2008). This enhanced the conveyance of river flows downstream and alleviated flooding upstream of the bridge (Dogpool Lane).

Figure 5: (A) The previous Dogpool Lane Bridge across the River Rea in which reinforcement blocks under bridge constricted high flows. (B) Replacement bridge in 2012 (reinforced without blocks) to allow high flows to continue downstream. Photos published with permission from the Selly Park South Neighbourhood Association (SPSNF, N.D.)

Following the 2016 flooding, an updated Preliminary Flood Risk Assessment was completed (complying with the requirements of the 6-year Flood Risk Regulations cycle) (BCC, 2017b). This was the basis for the development of Birmingham's 2017 Local Flood Risk Management Strategy, as well as implemented policy that gives Local Authorities a larger role in local flood risk management (BCC, 2017). This covered all aspects of predicting, managing, and responding to flood risk. Two flood storage alleviation schemes were also designed and implemented in Selly Park following the 2016 flood event, part-funded by the Environment Agency with support from local developers. The Selly Park South alleviation scheme includes the construction of an embankment upstream of the Dogpool Lane Bridge to retain water during extreme and intense rainfall (BCC, 2019). River Rea bank elevations were also raised below the bridge (BCC, 2019). The scheme protects ~200 properties in Selly Park South, many of which were damaged during the 2008 flood event (BCC, 2019). The separate Selly Park North alleviation scheme includes a flood storage area in Woodgate Valley on the Bourn Brook and the construction of a flood culvert under the Pershore Road (at the confluence of the Rea and the Bourn Brook) with overland flow route to direct flows to the culvert (BCC, 2019). This scheme is designed to a 1% (plus climate change) AEP standard of protection, and to reduce the flood risk in the Selly Park North area from very significant to low (Environment Agency, 2018).

The Selly Park South flood alleviation scheme was operational in 2018, prior to the 2018 flood event and successfully protected against property flooding from the River Rea (Environment Agency, 2018). However, the Selly Park North flood alleviation scheme only became operational in late 2019, following technical delays related to tunnelling under the Pershore Road (BBC News, 2018; Environment Agency, 2018), and was therefore not effective in reducing flooding in 2018. Since the 2018 flood event the potential to implement Property Level Flood Resilience (PLFR) and additional community and catchment flood mitigation (property flood walls and gates, drainage improvements, flood defence walls and banks, and additional flood storage areas) are also being considered (BCC, 2018).

While no protection measures failed during any event, a boundary wall installed between the 2008 and 2016 flood events resulted in exacerbating flood depths by impeding flood water drainage (BCC, 2016). The wall was modified after the 2016 flooding to reduce the flow impedance (BCC, 2016). There is no data or reports to suggest there have been any large changes to population density or land use changes and developments during this time.

Event comparison in respect to riverine flood hazard

Satellite precipitation data, which is available at 15-min intervals for 1km^2 squares across the city, suggest that rainfall during the three events (2008, 2016, 2018) was extremely intense, with the location of cumulative peak rainfall intensities corresponding closely with the areas inundated. The intense rainfall on the 5th and 6th September 2008 (**Figure 6**) was recorded at 34mm and 46mm respectively in Selly Park South (with a further 86.6mm recorded in the 6 days prior) (Clayton, 2008), with weather radar data indicating over 90mm in an hour over the Bourn Brook Catchment (Met Office, 2003). This followed already above average rainfall for August (Met Office, 2008; Met Office, 2010). Intense rainfall experienced between the 14th and 17th of June 2016 (**Figure 7**) recorded 111mm of rainfall over a 48-hour period for Selly Oak (slightly west of Selly Park) with around a quarter recorded during an hour (BCC, 2016). Heavy and intense precipitation was also experienced during the 2018 event on the 27th May, in which 81mm of rainfall was recorded in three hours at Winterbourne (slightly north of Selly Park), with more than half (58.6mm) falling in an hour (EA, 2018; Met Office, 2018). This was more than the Selly Park average monthly rainfall for May (62mm) (SPNFAG, 2018), and was larger than any rainfall event previously recorded for the Selly Park area (EA, 2018). Return period calculations for this rainfall event equal less than a 0.5% chance (greater than 1 in 200 years) (Environment Agency, 2018) although there are concerns that intense rainfall events of this nature are becoming more frequent over urban areas. Flooding in Selly Park from rainfall events is very localised and is an important consideration when considering rainfall radar data.

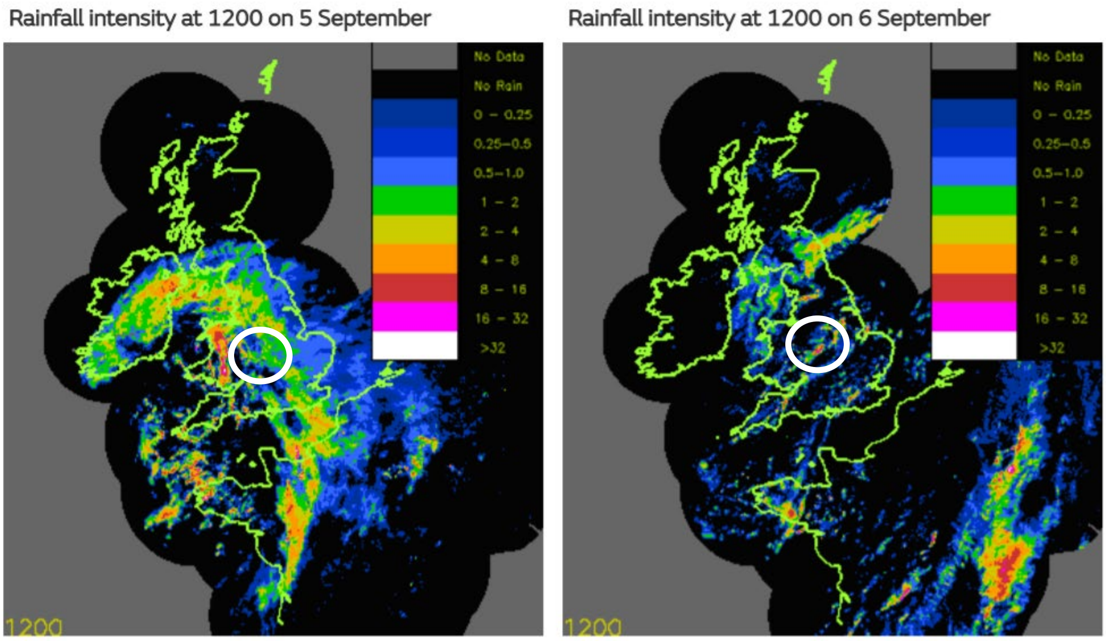

Figure 6: Intense rainfall (mm) experienced across the UK on the 5th and 6th of September 2008. Intense rainfall that occurred in Birmingham (circled) resulted in the localised 2008 flooding event. Contains public sector information licensed under the Open Government Licence v1.0 (Met Office, 2008)

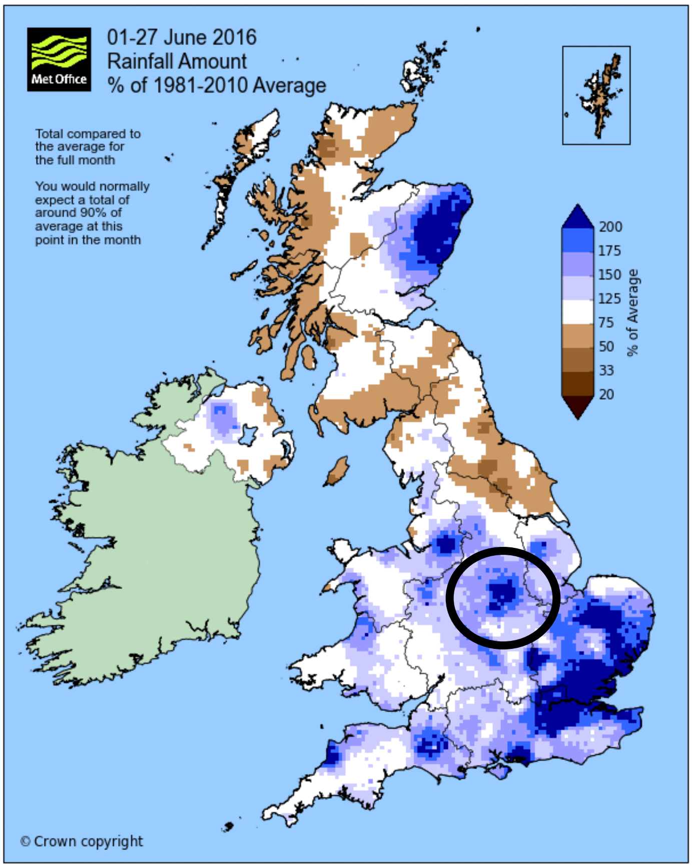

Figure 7: Average rainfall for the UK during June 2016, resulting in localised flooding across Birmingham (circled). Contains public sector information licensed under the Open Government Licence v1.0 (Met Office, 2016)

While there was some local 'pluvial' flooding, most properties in Selly Park experienced riverine (fluvial) flooding as rainfall is rapidly routed through the storm drainage network to local rivers (the Rea and the Bourn Brook). In some cases, the first component of the floodwaters comprised sewage (as the city has a combined sewer and storm drainage network). Hence the flood events were the product of local rainfall, that was rapidly routed through the storm drainage network to the (small) urban rivers, supplemented by the discharge from Combined Sewer Overflows (CSOs).

Flow data from the River Rea gauge station, downstream of Selly Park and the River Rea-Bourn Brook confluence, show there was only a slight difference between flow during the 2008 and 2016 events. Flow data are only available from April 1967, and so statistical data on recurrence intervals for peak river flows are unreliable, however recorded flows for the three events were 71.9 m^3/s (2008), 73.6 m^3/s (2016) and 82.3 m^3/s (2018) (**Figure 8**) (recorded by the National River Flow Archive NRFA). Mean daily flow is recorded as 0.749 m^3/s. Modelled flood frequencies for the Bourn Brook (source of fluvial flooding for Selly Park North) suggest the 2018 flood event had an AEP of 2% (a 1 in 50 year return period), compared to the 2016 event that had an AEP of 5% (a 1 in 20 year return period) (EA, 2018). However, there is only medium confidence for these modelled flow return periods in the Bourn Brook. Although the model provides some confidence for flows in the Bourn Brook and Rea Catchment (from a comparison of gauge station observed levels and existing flood records), a lack of historical observed flow and rainfall data and overland flows in urban flooding make it difficult to confirm the model results for complex urban environments (Smith, 2007).

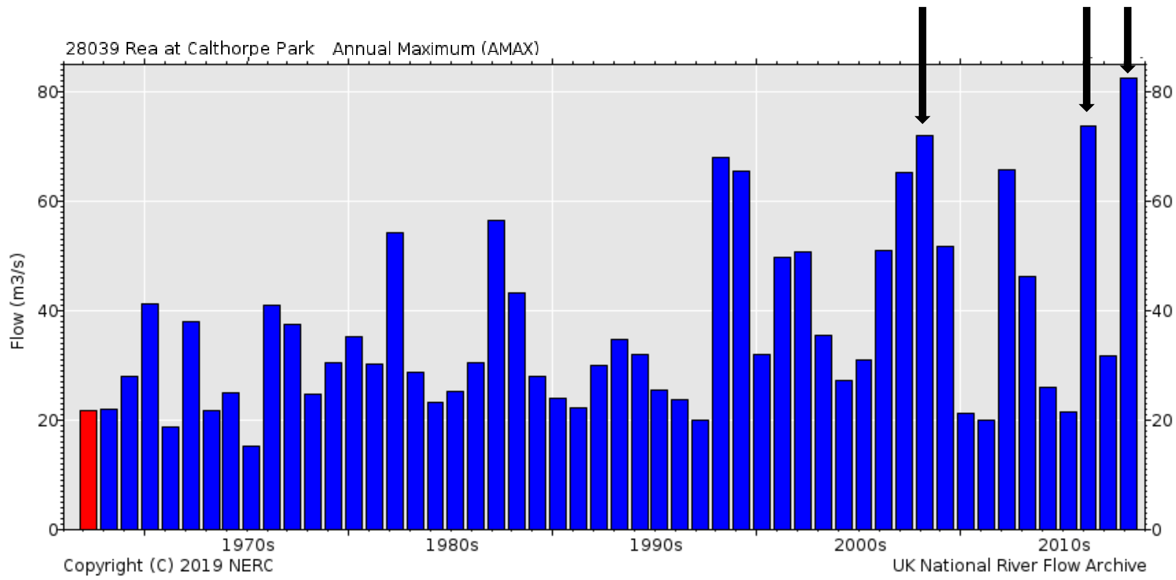

Figure 8: Annual maximum peak flow data showing the 2008 (71.9 m^3/s), 2016 (73.6 m^3/s) and 2018 flooding events (82.3 m^3/s). Data from the UK National River Flow Archive (NFRA, n.d.)

Event comparison in respect to exposure

The areas affected in Selly Park (both North and South), are predominately residential, urban areas with dense Victorian, largely terraced housing (dating from around 1900). The same residential streets in Selly Park North and South were exposed during the 2008 and 2016 flood events. The Selly Park South alleviation scheme was operational during the 2018 flooding which successfully reducing property exposure to riverine flooding in Selly Park South. While there were still property and road flood incidents, these were primarily from surface-water flooding. Delays to the Selly Park North alleviation scheme meant Selly Park North residential areas were still largely exposed to flood flows from the Bourn Brook.

Event comparison in respect to vulnerability

There is little recorded information on the flood vulnerability of Selly Park. However, a collaboratively developed Flood Vulnerability Index tool for the UK (that considers census data for vulnerability factors) suggests Selly Park has a 'relatively low' vulnerability score (Sayers *et al.*, 2017). Based on these data, the area is identified to have a (UK-based) average or better ability to recover, vulnerability due to income and community support ranged. However due to minimal warning times associated with localised flooding the area has a 'relatively high' inability to prepare and inability to respond (Sayers *et al.*, 2017). To reduce the vulnerability to these sudden events, awareness of flood risks is highlighted as an important factor by Birmingham City Council. Raising awareness and communicating level of risk is continually included in Strategic Flood Risk Management Plans (2012) and the Local Flood Risk Management Strategy (2017). Drop-in sessions and events that enable opportunities to provide the community with information on their flood risk are also largely used (BCC, 2018b), particularly following the 2016 flood events and when providing details on the two Selly Park alleviation schemes (EA & RCP, 2016). Following the 2008 flood events warning services for Selly Park were improved (BCC, 2012). However, there is no data that suggest whether these have successfully increased awareness.

In addition to Local Authority strategies to increase flood awareness, community level awareness raising has also been apparent by the Selly Park Community Association and Flood Action Groups, primarily in Selly Park South, that undertake group meetings to discuss flood risk and distribute 'Flood Information Packs' to the surrounding community (SPSFAG, 2010). This was particularly the case for Selly Park South, whose flood action group (Selly Park South Flood Action Group SPSFAG) formed in response to the 2008 event (SPSAG, 2010). Community reports suggest that initial responses to all flood events in Selly Park South have been community led. The SPSFAG worked with key stakeholders (Local Authority, Seven Trent Water, the Environment Agency and West Midlands Fire and Police Services) to create a 'Selly Park South Flood Action Plan' and install an additional river level gauge by Dogpool Lane (linked to Environment Agency Flood Warning System) (SPSFAG, 2010). The flood action plan covers requirements both during floods (protecting properties, assisting elderly residents, and evacuation plans) and flood recovery following events. During the 2016 flood, residents worked with the SPSFAG and the City Council to defend properties with sandbags and other temporary defences (SPSNF, 2016). This community response continued in the 2018 event with residents in Selly Park South, who had experienced earlier flood events (2008, 2016), implementing makeshift property defences, while the SPSFAG provided assisted residents by providing Hydrosnakes (hygroscopic flood defence sacks) and airbrick covers (purchased by the SPSFAG with a grant from the city council) to vulnerable properties (against surface water flood risk as no fluvial flooding was reported) (Clayton, 2018). However, delivery of sandbags during the 2018 event was prevented by traffic delays due to inundated roads (SPSNF, 2018). An additional Selly Park North Flood Action Group (SPNFAG) was formed following the 2018 flooding (through the Selly Park Community Association) (BCC, 2017; SPNFAG, 2018).

Damage to properties during the 2008 and 2016 events is reported to have resulted in ~60 people living elsewhere while their properties were repaired (BBC News, 2018). It is reported that some residents had only recently moved back into their properties or completely repaired damages that occurred during 2016 flooding before they were inundated again in the 2018 flooding (BBC News, 2018). The short duration period between the 2016 and 2018 floods may therefore have reduced coping capacity (as people were still dealing with damage from earlier floods). In terms of general capacity to cope with flood events, the Bourn Brook and Selly Park areas are in one of the least deprived wards in the city of Birmingham (rank 61 out of 69 based on 2015 index of deprivation, 2011 census data). However, employment and income are reportedly low due to the high proportion of students (56.6% aged between 18-24, 2011 census data) (BCC, 2016b). There has been no information reported on the long-term effects of the flooding in Selly Park.

Insurance is an important component of UK flood risk management and is provided and dominated by the private market sector (Penning-Rowsell et al., 2014). The government FloodRe scheme (implemented in 2013) seeks to ensure that flood cover is available and affordable to properties in high flood areas or those that are often flooded (Penning-Rowsell et al., 2014; Flood Re, 2019). The completed alleviation schemes in Selly Park have reduced the chance of flooding and its classification to low. This may impact the insurance cover provided to residents with the FloodRe scheme but may reduce insurance costs with other private insurers (Environment Agency, 2016 through the Selly Park Residents Community Association).

Summary

In summary, all three events are comparable in terms of flooding causes and flood magnitude, but with differing impacts that reflected recently implemented flood management measures. All events were caused by intense rainfall that rapidly flowed into the local watercourses, the River Rea and Bourn Brook (BCC, 2018). This led to localised flooding in urban, residential areas on the floodplain of the River Rea and near the confluence of the Rea and the Bourn Brook (Selly Park North from the Bourn Brook and River Rea, and Selly Park South from the River Rea) (BCC, 2015). Following each event flood risk management actions were taken, driven largely by a rise in awareness by the community interventions and work by associated groups (Selly Park Community Association, SPSFAG and SPNFAG) (medium confidence), as well as the Local Authority, Birmingham City Council. Two large flood alleviation projects (Selly Park North and Selly Park South alleviation schemes) have also subsequently been built to reduce the flooding and related impacts and damages in Selly Park, as well as construction works to bridge infrastructure (Dogpool Lane Bridge) and raised flood defences (Environment Agency & RCP, 2016). While recorded river and flood flows were comparable for each event (albeit with slight increases over time), the number of properties damaged and inundated have decreased. This decreasing impact has mainly resulted from a reduced exposure following the flood management schemes, particularly for Selly Park South (limited reports of flooding damages in SPS in 2016 but Dogpool Lane Bridge developments are suggested to have reduced the local impact - limited/medium confidence; 2018 flooding after operational alleviation scheme resulted in no properties inundated by riverine flooding – strong confidence). Selly Park North has a less clear pattern of decreasing flood impacts, but fewer properties were flooded in 2018 than 2016 (2016 had a larger impact). In terms of community preparation and response, since the 2008 flood event surprised the Selly Park area, the community have worked together to increase flood warning in the area (installing additional river level gauge and more awareness) and protecting homes at property level when these warnings are issued (SPSNF, 2016; SPSNF, 2018; Clayton, 2018). The frequent flooding events have resulted in strengthened roles and investment in flood management by Birmingham City Council and the Environment Agency to reduce exposure and increase awareness and responsibility by the community to protect their properties. This illustrates the Adaptation Effect, where frequent events reduce vulnerability (Kreibich *et al.*, 2017). However, the frequency of events and time between the 2016 and 2018 flood events (less than two years) meant that some residents had only just returned to their properties and/or were still dealing with previous damages, and therefore may have reduced the coping capacity for these individuals.

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ID 30

Paired flood events: Selly Park, Birmingham (UK), Paired Riverine and Pluvial Flood Events: 2008, 2016, 2018

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Since this report covers three events, it is identical to report of ID 29, please see pages 197-214.

ID 31

Paired riverine flood events: 2011 and 2014 riverine floods in the Assiniboine River Basin in Canada, North America

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Short description of both events with a focus on impacts

In the early 21st Century, two record-breaking flood events occurred in the Canadian Assiniboine River Basin (ARB) only 3 years apart. In 2011, a wet fall, above-normal winter snowpack and above-normal precipitation in April, May and June combined to produce one of the most severe floods in Canadian history (Blais et al., 2016). Three years later in 2014, heavy summer precipitation caused significant flooding in late June and early July, the first time in modern records that a major flood in the region was caused by summer precipitation (Ahmari et al., 2016).

Estimates of monetary impacts are similar between both events, exceeding $1 B CAD (all estimates are in 2014 dollars). Specifically, the 2011 event had an estimated total cost of $1.25 B CAD (MIT, 2013) while the 2014 cost was estimated at $1.16 B CAD (Canadian Disaster Database). This total cost includes $117 M in repairs to provincial roads and bridge sites in 2011 (MIT, 2013), and $200 M in provincial infrastructure repair costs in 2014 (Ahmari et al., 2016). In terms of requests for funding under the Canadian Disaster Financial Assistance Arrangements (DFAA) program, the Province requested $815 M in 2011 and $180 M in 2011 (Kavanagh and Annable, 2017). The 2011 flood lasted up to 3 months in some areas, causing significant infrastructure impacts with more than 1250 roads and bridges damaged and 7100 evacuees, primarily from Indigenous communities (MIT, 2013). In particular, the Lake St. Martin First Nations community was nearly destroyed, and many residents were not able to return until 2017 or later after the community was rebuilt (Grabish, 2017; Lambert, 2018). In 2018, a judge approved a $90 M payout in a class-action lawsuit against the Government of Manitoba by four First Nations evacuated in 2011 (Lambert, 2018). In 2014, due to the later timing of the event, impacts were more severe for the agricultural industry, with over 3.5 M acres either unseeded or flooded in Manitoba (CBC News, 2014) and an additional 3 M acres unseeded or flooded in Saskatchewan (Ahmari et al., 2016; AAFC 2014). $21 M in damages to the ranching industry in the vicinity of Lake Manitoba was documented in 2011; and $10 M in 2014 (Westdal et al., 2015).

For comparison purposes, the analysis below focuses on impacts within Manitoba, although flooding did affect other jurisdictions such as Saskatchewan and the northern United States.

Descriptions of processes between events with a focus on risk management

Overall, although there were several new management processes initiated between the 2011 and 2014 flood events, based on the evidence, we assessed that there was limited time to make significant impactful changes due to the short 3-year time period between events. As a result, the 2014 event served to highlight many of the same vulnerabilities in the Manitoba flood protection system (KGS, 2016). However, due primarily to the operation of the Fairford Water Control Structure and the construction and operation of the Lake St. Martin Emergency Outlet Channel (described below), we rated the change as a slight increase between 2011 and 2014. Management processes of note that occurred between 2011 and 2014 included:

- **Major studies to improve flood mitigation and management along the Assiniboine River in Manitoba.** Much historic flooding in Manitoba took place in the Red River Basin, thus the significant flood of 2011 in the ARB incited major renewed efforts to improve flood management in this portion of the province. The flood of 2011 prompted the development of a surface water management strategy and several studies on flood risk management, such as the Manitoba 2011 Flood Review Task Force Report (MIT, 2013), the Lake Manitoba and Lake St. Martin Regulation Review Report (Westdal et al., 2013), and the Assiniboine River and Lake Manitoba Flood Mitigation Study (KGS, 2016). However, the recommendations from these reports were not available until directly prior to or post the 2014 flood event, limiting the ability to act on lessons learned from 2011.
- **The construction and operation of the Lake St. Martin Emergency Outlet Channel (LSMEOC).** During the summer of 2011, Manitoba constructed an emergency channel between Lake St. Martin and the Dauphin River to reduce the risks from frazil ice formation and drawdown lake levels in Lake Manitoba and Lake St. Martin. The LSMEOC operated over the winter to prepare for the 2012 spring runoff period (MIT, 2013). During the floods of 2014, the LSMEOC was again opened to one-third of its operating capacity in early July 2014 and provided a significant flood reduction benefit. The channel continued operating over the winter season (Government of Manitoba (a), n.d.). As an emergency structure, the LSMEOC can only be operated under a state of emergency. Following the 2011 floods, it was recommended that the LMEOC become permanent, and the Manitoba government announced its intention to do so, but the licensing process did not start until after 2014 (Westdal et al., 2015; Government of Manitoba (b), n.d.).
- **A change in the unofficial design standards for flood protection.** Policy under the Provincial Planning Act (Regulation 81) requires flood protection to the 100-year flood level or highest flood on record. The Province introduced 'interim' flood protection levels following the 2011 floods (Westdal et al., 2013), and the Manitoba 2011 Flood Review Task Force (MIT, 2013) recommended an increase in the provincial standard to a 200-year flood level (as opposed to the standard practice of recalculating a 100-year flood based on the latest flood record). While this standard has yet to be introduced in legislation, it is now the unofficial practice of water managers to build to a 200-year flood standard (pers. comm. *Patrice Leclercq, KGS 2020).* For example, the official assessment of flood mitigation options commissioned by the Province of Manitoba required the assessment of vulnerabilities against a 200-year event (KGS, 2016). However, infrastructure changes to adhere to this standard were not made prior to 2014 as technical studies were still ongoing (KGS, 2016).
- **Modification to Operating Rules on the Fairford Water Control Structure (FRWCS).** The FRWCS operates on the outlet from Lake Manitoba into the Fairford River. In 2012, the Lake Manitoba/Lake St. Martin Regulation Review Committee (Westdal et al., 2013) made several recommendations regarding the regulation of Lake Manitoba and the FRWCS that the Province later implemented (Westdal et al., 2015). However, lake levels remained so high for several years that only one is relevant to management between 2011-2014: During recovery from flood conditions on Lake Manitoba, the FRWCS is kept wide open until Lake Manitoba recedes to the middle of the range. As such, the FRWCS operated for maximum possible discharge between 2011 and 2014 to lower the lake level as much as possible (Ahmari et al., 2016).
- **Spending on personal and community flood mitigation activity via the Flood 2011 Building Recovery and Action Plan BRAP** (Wetsdal et al., 2013; Government of Manitoba 2011). Following the flood of 2011, the Government of Manitoba established a one-time $175 M special compensation package (BRAP) to fund several

compensation packages and flood mitigation works. The Manitoba Agricultural Services Corporation (MASC) and Manitoba Agriculture, Food and Rural Development (MAFRD) were given the responsibility of administering emergency assistance programs announced under BRAP. Some BRAP sub-programs focused on compensation, while others provided financial assistance to producers and homeowners to invest in flood mitigation activities. We estimate, that between 2011-2014 approximately $47 M was spent on the mitigation aspects of the program (MASC, 2014)*. Financial assistance provided to mitigation aspects of the program by March 31, 2014 included Lake Manitoba Financial Assistance Program Part B ($30.738 M CAD) and Part D ($8.312 M CAD), the Lake Dauphin Emergency Flood Protection Program ($353 K CAD) and the Shoal Lakes Agricultural Flooding Assistance Program ($5.303 M CAD). 5.5% in administration costs were added to this cost estimate as per MASC (2014). Under a sub-program of BRAP which allowed producers to voluntarily sell chronically flooded land, MAFRD made at least 54 land purchases between 2011 and 2014 (MAFRD, 2014).

Event comparison in respect to riverine flood hazard

Major differences between the 2011 and 2014 events include the nature, length and timing of the events. The 'flood without precedent' of 2011 was a typical flood for the ARB in that it was a result of spring melt, and with continued spring and summer precipitation, flooding lasted up to 3 months in some areas. In 2010, above-normal fall precipitation (150-200%) over wide ranges of Manitoba and Saskatchewan contributed to soil moisture levels 100-250% of the long-term average (MIT, 2013). Further, a relatively high winter snowpack, varying geographically in the region between 90-130% of normal snow water equivalent and low winter temperatures caused significant frost penetration. These antecedent conditions to the 2011 event lowered the ability of the soil to absorb high volumes of spring snowmelt and increased runoff volumes during precipitation events in May, June and July (Blais et al., 2016). In addition, several major rain systems with large spatial extents and some smaller systems in late April, May and June produced record high water levels. The first flood peak occurred due to a combination of snowmelt and rainfall in early May (Blais et al., 2016). The 2014 flood was unique in modern records for the basin, arising chiefly from major summer precipitation events. Antecedent precipitation conditions in the preceding fall and winter were relatively normal (Ahmari et al., 2016). A cool spring delayed snowmelt in many areas until late April, so that soils and prairie wetlands were saturated (Szeto et al., 2015) when a trend of heavy precipitation began (AAFC, 2014). Between the beginning of April and end of June, regions of the ARB received 175-350 mm (115-200% of average) (AAFC, 2014). Then, two major systems in June (the 13-23 and 28-30) in the headwaters of the ARB led to flood peaks starting early July (Ahmari et al., 2016; AAFC, 2014; Szeto 2015) [Figure 1 and Figure 2, Appendix A]. The severity of the resulting floods in 2011 and 2014 in terms of flood peaks is comparable at various points along the ARB [Figure 3 and Figure 4, Appendix A]. In general, the 2011 event was more hydrologically severe in the lower ARB, while the 2014 event was more hydrologically severe in the Upper ARB (Blais et al., 2016; Ahmari et al., 2016). Overall, however, we assessed the hazard as decreasing slightly between the 2011 and 2014 events due primarily to the length of the 2011 event (up to 3 months). Due to the length of flooding in 2011, and the subsequent diversion of 5.9 M dam^3 of water through the Portage Diversion, Lake Manitoba and Lake St. Martin peaked at 249.1 m and 245.55 m respectively, more than a meter above flood stage.

Event comparison in respect to exposure

According to the Assiniboine River Basin Initiative, the ARB covers about 162,000 km^2 with about 1.5 M people. Due to the large geographical expanse of the flood events, specifics around the overall exposure of people and assets for each event is not well known (Westdal et al., 2015), and therefore there is limited evidence to comment on exposure. However, *spatial* exposure was *likely* similar between both the 2011 and 2014 events due to the short time between both events. There was a difference in *temporal* exposure between the events, with the former lasting up to 3 months in some areas. This meant that significantly more water was diverted through the Portage Diversion, raising the levels of Lake Manitoba and Lake St. Martin 0.76 m and 0.4 m higher, respectively, in 2011 (Ahmari et al., 2016).

Reported and aggregate data are not directly comparable for affected roads and structures, and very limited for 2014, although on the surface it appears similar numbers were affected. The 2011 flood affected 154 provincial roads and highways, 500 municipal roads, damaged 73 highway provincial structures and 500 municipal bridges (MIT, 2013). In 2014, about 247 provincial road segments were closed or had a 'caution' status (Bereza and Thomson, 2014) and there were impacts to >100 provincial bridge structures (Hengen et al., 2015). Approximately 30 bridges or culverts in southwest Manitoba were identified as needing replacement, with another 50 structures needing significant repairs (Ahmari et al., 2016).

Significantly more people were evacuated in 2011 (7001) relative to 2014 (800), which suggests more people were exposed, but many people in communities along Lake St. Martin were still displaced when the 2014 floods occurred (MIT, 2013; Government of Manitoba, 2014; Grabish, 2017). Numbers for farming land exposed are more robust and comparable and emphasize the difference in the timing of the events. Overall affected acres of farmland are slightly more in 2014 (3.5 M versus 3 M in 2011). 3 million acres of cultivated farmland went unseeded in 2011 (MIT, 2013) relative to 950,000 in 2014. However, approximately 2.5 million seeded acres were flooded in 2014 (AAFC, 2014), and ultimately, the agricultural losses in 2014 were higher due to the later timing of the event and lack of time to engage in agricultural recovery activities (Annable, 2014).

A key hotspot area exposed in both flood events was the City of Brandon, located downstream from where the Qu'Appelle River meets the Assiniboine River. The recorded peak flows at Brandon, were slightly higher in 2011 (Ahmari et al., 2016), and flooding lasted nearly 120 days in Brandon in 2011 as well (Blais et al., 2016). The shores of Lake Manitoba, Lake St. Martin and Dauphin River were also exposed to some of the worst impacts of the flood in both 2011 and 2014 (MIT, 2013; KGS, 2016). Between 2011 and 2014 the Province made 54 voluntary land purchases in the chronically flooded Shoal Lake region beside Lake Manitoba (MAFRD, 2014). Thousands of residents from Indigenous communities such as the Lake St. Martin, Dauphin River, Little Saskatchewan Pinaymootang First Nations, around the lakes were displaced for years following the first event (Grabish, 2017; Lambert 2018). Thousands remained displaced for multiple years, requiring approximately $1.6 M/month in funding for support (Muter, 2019). In 2018, four First Nations were successful in receiving a settlement of $90 M in compensation from the Manitoba and Canadian Governments (Muter, 2019).

Ultimately, while there is limited evidence for number of people and assets exposed, the comparable numbers we could identify led to an overall rating of 'no change' in exposure between 2011 and 2014.

Event comparison in respect to vulnerability

There was a substantial difference in awareness between the 2011 and 2014 flood events. In the case of the former, the Province recognized early in the fall of 2010 that there would be major flooding throughout Manitoba and issued the first spring flood outlook with a high flood risk warning in January (MIT, 2013). The Manitoba Emergency Measures Organization began planning well ahead of the flood event, and the Province took many actions including the establishment of the Manitoba Emergency Coordination Centre, purchasing two additional sandbag machines, and raising and reinforcing dikes along the flood route (MIT, 2013; Blais et al., 2016). In 2014, the spring flood outlook predicted only minor to moderate risk (Ahmari et al., 2016), and the Province had much less time to prepare for the flash flooding that occurred later in the summer as this was a non-typical event for the basin (Healy, 2014). Several deficiencies in the flood forecasting system used by Manitoba were identified in the case of the 2011 event, particularly the inability to provide reliable rainfall-runoff forecasts (MIT, 2013). Likely, these deficiencies also hindered the Provincial ability to respond to floods generated by major precipitation events, such as the 2014 flood.

Despite the difference in awareness, there was some similarity between the organizational emergency management and coping capacity between the two events due to the short period between them. The Canadian military was deployed in both 2011 and 2014 to reinforce provincial emergency capacity to respond. Emergency management was recognized as adequate to outstanding in both cases (MIT, 2013; KGS 2016), including the skillful operation of flood protection infrastructure such as the Portage Diversion, which was operated above capacity without damage to the infrastructure for several weeks in 2011 (MIT, 2013; Blais et al., 2016; Ahmari et al., 2016). Later studies suggested that emergency management vulnerability could be reduced through additional prior planning and documentation, particularly in the case of more serious and cost-incurring responses such as mass evacuations from highly populated centers (KGS, 2016).

Some evidence to suggest increased preparedness between events. First, between 2011-2014 approximately $47 M was spent on community and personal level mitigation funding programs and 54 government land purchases were made (MASC, 2014; MAFRD, 2014). This suggests individual land and homeowners may have been more prepared come 2014. Second, infrastructure such as the Fairford Water Control structure and the Lake St. Martin Emergency Outlet Channel were operated differently between and during events to reduce flooding impacts. The successful operation of previously installed or temporary flood protection infrastructure is largely credited with the mitigation of the worst impacts of the flood downstream (Blais et al., 2016), and overall, MIT (2013) estimates that impacts on the lower ARB would have surpassed $2.2 B CAD without the flood protection infrastructure [Figure 5, Appendix A].

Overall, however, the province made many preparations in 2011 that were used again in 2014. These actions included raising and reinforcing approximately 190 km of dikes, successful operation of the Shellmouth Dam and the Portage Diversion above design capacity for an extended period, and the construction of an emergency controlled breach at Hoop and Holler and outlet channel from Lake St. Martin (MIT, 2013). Many of the same strategies were used in 2014 (Ahmari et al., 2016), except for the controlled breach at Hoop and Holler, as officials determined that that was not required (Westdal et al., 2015). However, due to the short period between the event, the floods of 2011 and 2014 highlighted the same vulnerabilities in the flood protection system (KGS, 2016). Specifically, a follow-up study by KGS (2016) identified over

100 vulnerabilities in the system, including that the lower ARB is protected to a standard below the minimum criteria for flood protection promoted by the Province, and that the shorelines of Lakes Pineimuta and Lake St. Martin are particularly vulnerable to flooding. Indigenous communities are particularly vulnerable due to isolation and lack of resources (MIT, 2013). Further, a follow-up study on provincial flood protection infrastructure identified widespread dissatisfaction with the operations of the Portage Diversion, which effectively mitigated flooding in the Lower Assiniboine at the expense of communities and assets around Lake Manitoba and Lake St. Martin (Westdal et al., 2015).

Overall, we assessed vulnerability as slightly increasing between 2011 and 2014, largely due to the nature of the event being non-typical for the basin, and the resulting lack of warning and preparedness relative to 2011.

Summary

Overall, this paired event case study supports many of the conclusions drawn by Kreibich et al. (2017) regarding short duration time lags between flood events, namely limited changes in exposure and lack of time to make major structural changes. In the case of the ARB, there is much more robust data available for the 2011 flood event, and it is often difficult to find directly comparable data.

In general, this analysis provides some support for the adaptation effect (Di Baldassarre et al. 2015), particularly when this paired event case study is put in the context of historical adaptation to floods in Manitoba. Manitoba is located downstream of three major river systems (Saskatchewan River Basin, Assiniboine River Basin and Red River Basin), and has extensive historical experience with major flood events (MIT, 2013). These major events, such as the 1950 and 1997 "Flood of the Century" in the nearby Red River Basin, have prompted significant investments in flood protection infrastructure and operations such as the Red River Floodway, Portage Diversion, and Fairford River Water Control Structure (outlet from Lake Manitoba) (Westdal et al., 2015; MIT, 2013). These works mitigated the impacts of both the 2011 and 2014 flood events (Blais et al., 2016; KGS 2016). Part of the vulnerability that emerged in the 2011 floods was due to the effort that has historically concentrated on the Red River Basin (such as building higher dikes, etc.), which was the site of the 1997 and 1950 floods, rather than the Assiniboine (MIT, 2013). Later studies identified particularly vulnerable regions in other Manitoba watersheds, such as the Lower Assiniboine, Dauphin Lake, Lake Manitoba and Lake St. Martin. However, flooding in the latter three locations has been identified as a "chronic problem" (KGS, 2016). The fact that mitigation efforts have not taken place in these locations, despite experiencing frequent flooding, is beyond the scope of this analysis.

In terms of the hazard itself, there is evidence to suggest that climate change and human management played a role in exacerbating the severity. Climate change trends are not always easy to detect against a background of natural climate variability and human management. In the ARB, wetland drainage in the western Canadian prairies has decreased water storage potential on the landscape, and these land-use changes have increased flood peaks in the 2011 and 2014 events (Pomeroy et al., 2014). However, several studies show evidence that a change in the hydrologic regime in regions of the basin may be underway (Shook and Pomeroy, 2012; Dumanski et al., 2015), and research indicates that future changes could include more rainfall generated flood events, and rain on snow events (Bonsal et al., 2019). The difference in awareness and preparation between the two events due to the unprecedented nature of the flood hazard underlies that increasing vulnerability in the 2014 event.

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Appendix A: Accompanying Figures

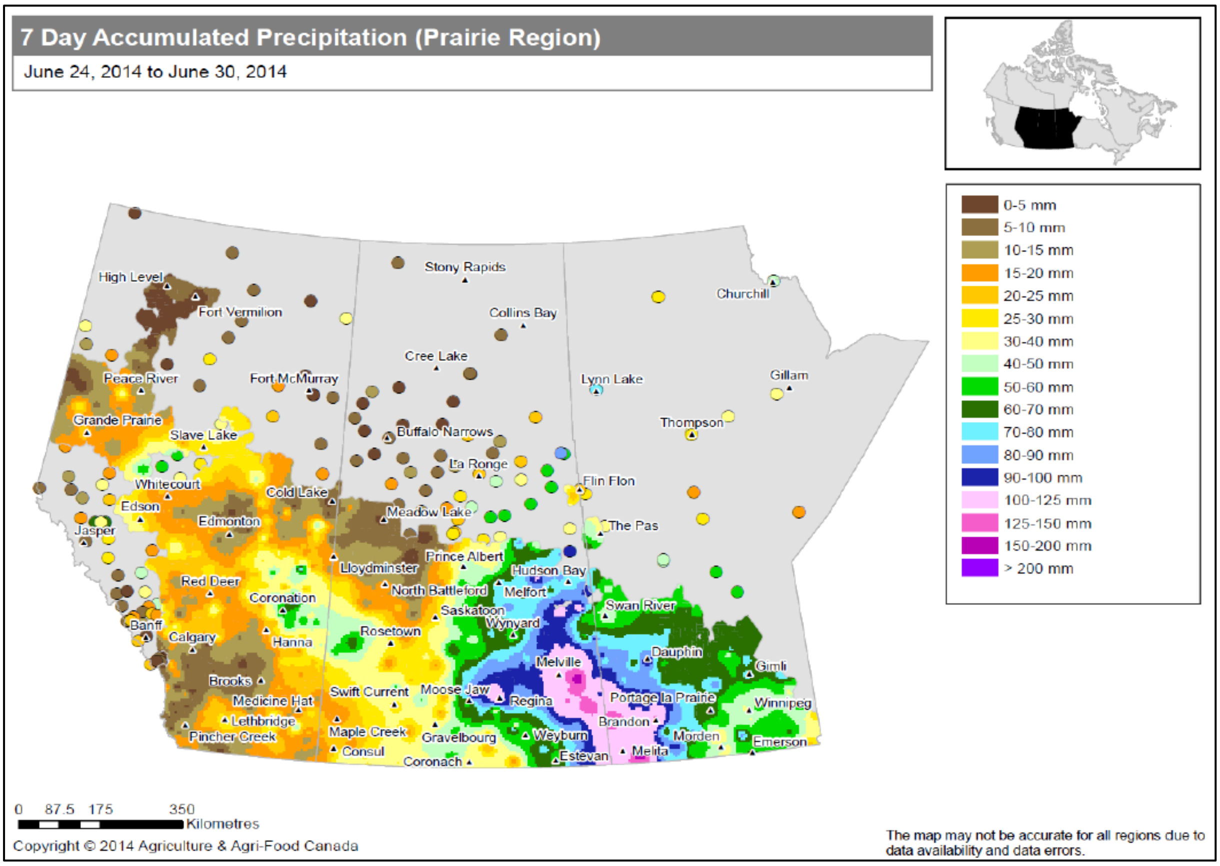


Figure 1: 7-Day Accumulated Precipitation in the Prairie Region, Canada (Source: AAFC)

Figure 2: Percent of Average Precipitation May-June 2011 (top) and 2014 (bottom) (Source: AAFC)

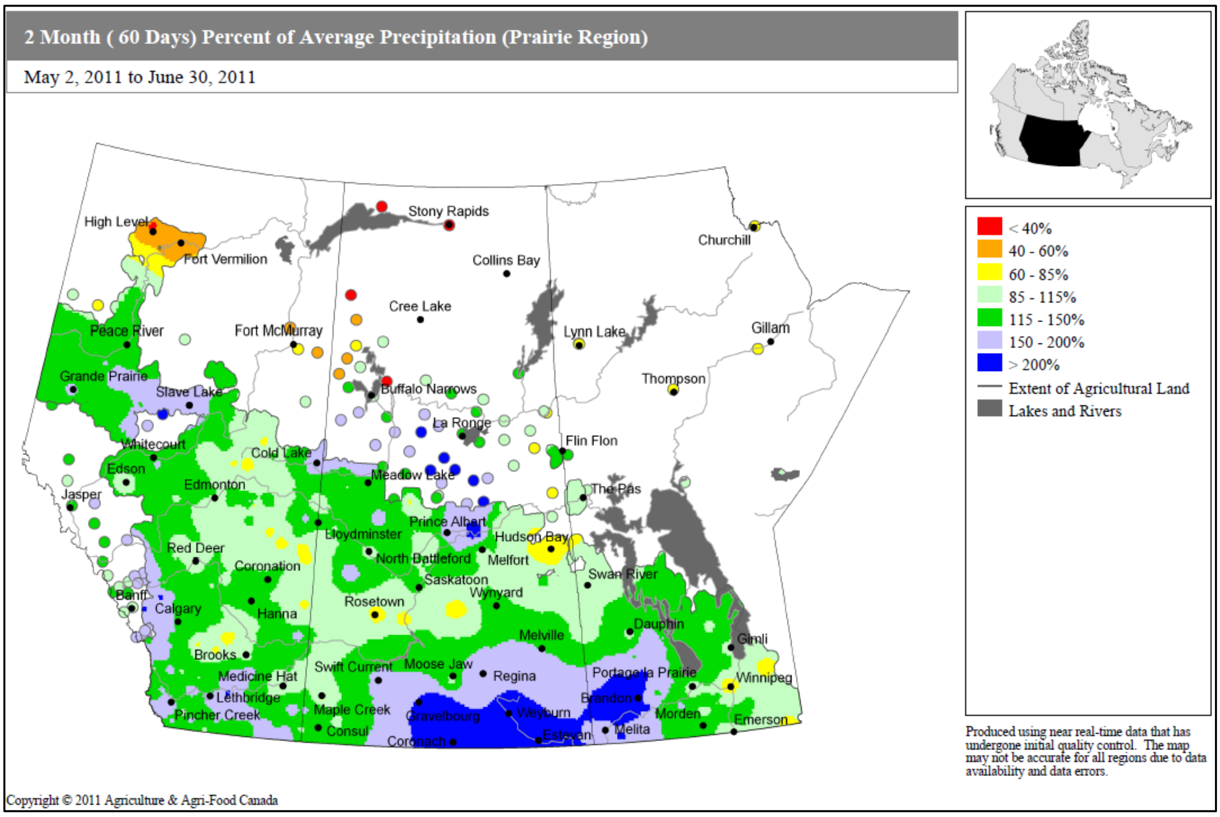
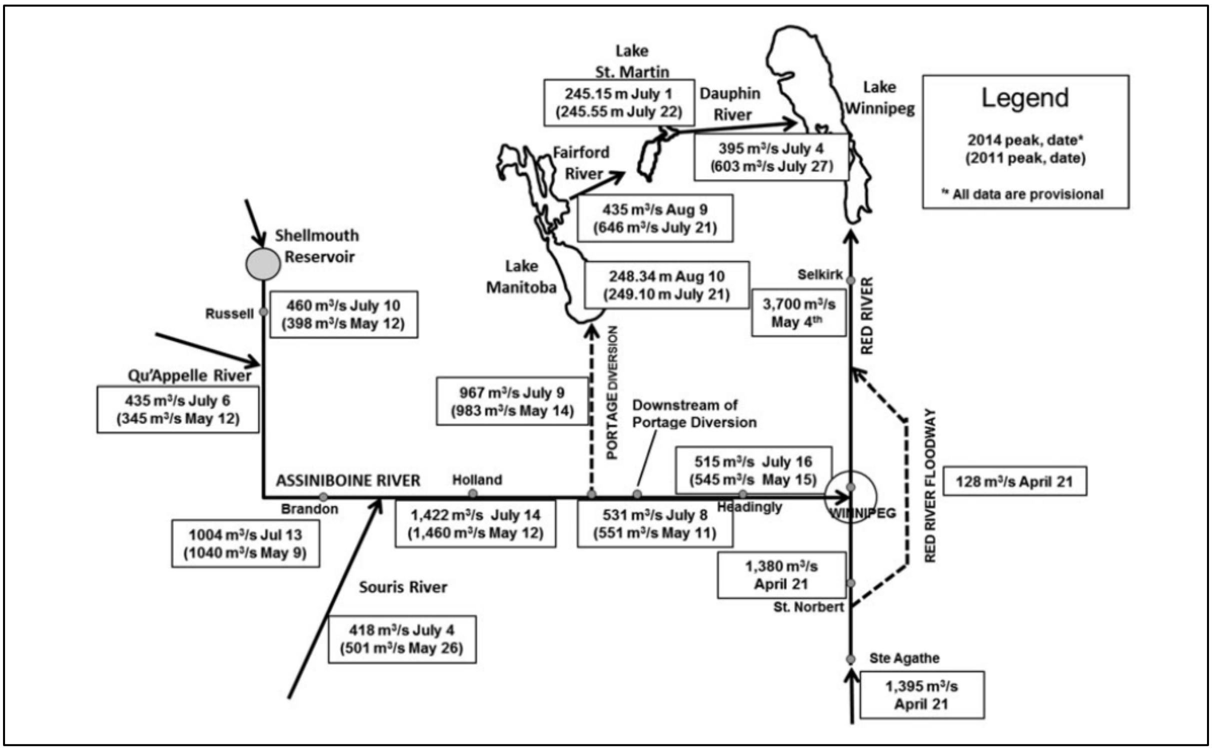


Figure 3: Peak Flows and levels for the 2014 and 2011 floods in the Lower Assiniboine Watershed



(Source: Blais et al. 2016)

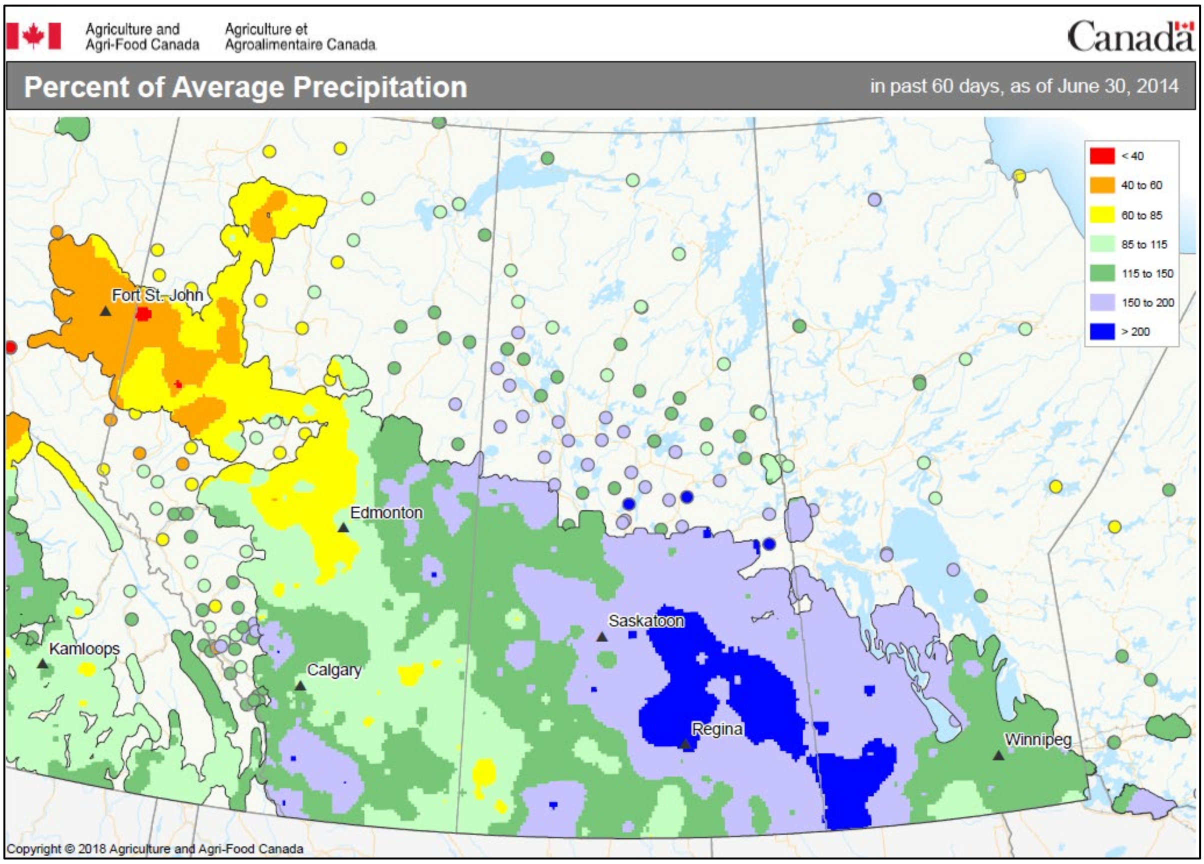


Figure 4: Peak Flows and levels for the 2011 and previous record peak floods in the Lower Assiniboine Watershed (Source: Ahmari et al. 2016)

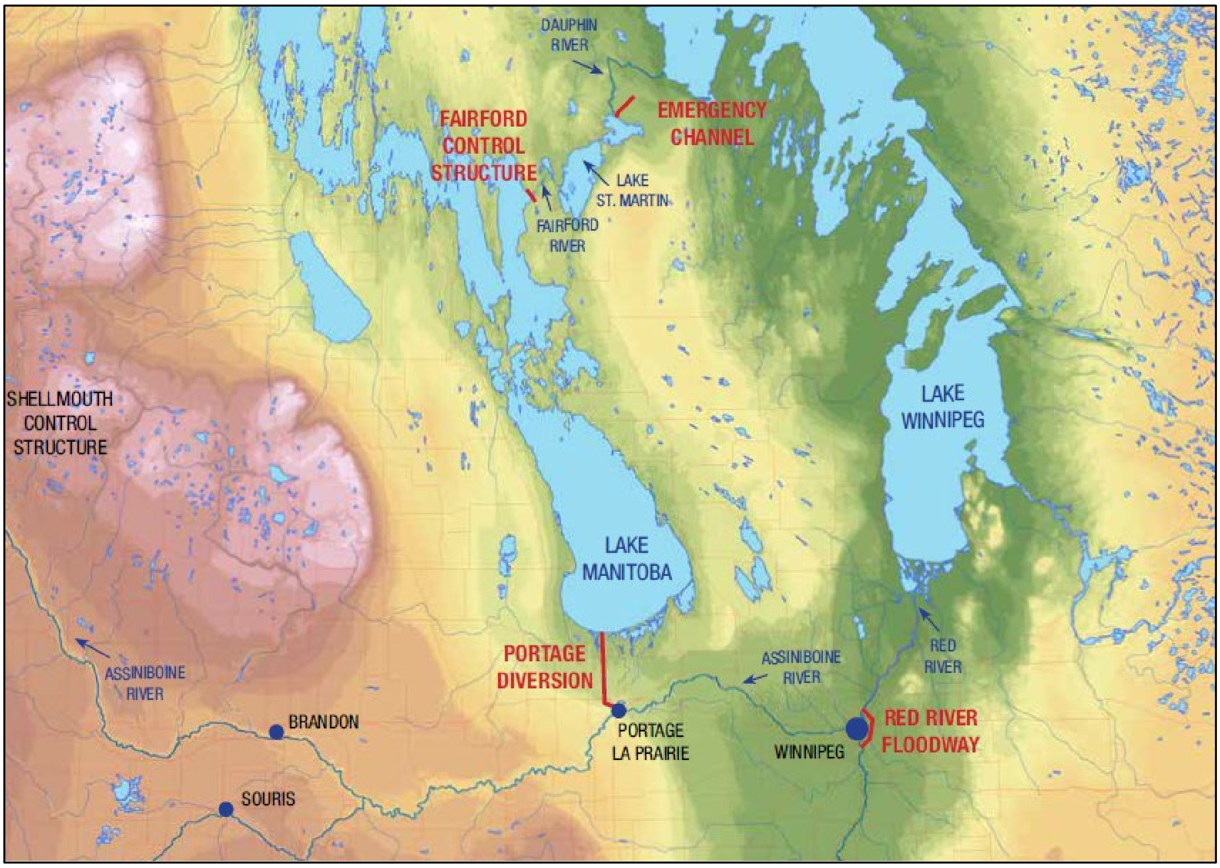
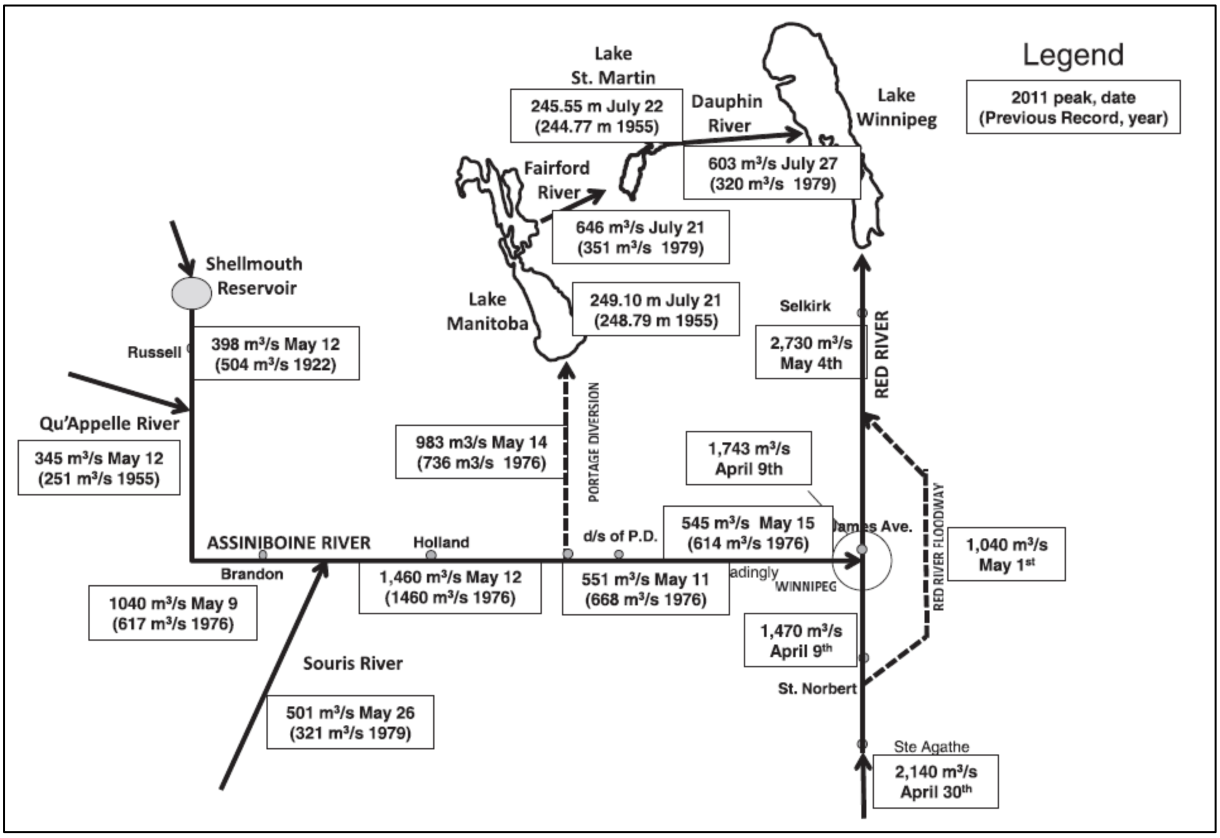


Figure 5: Manitoba Flood Control Structures (Source: Westdal et al. 2015)



ID 32

Paired riverine flood events: 2011 (event-year1) and 2016 (event-year2) riverine floods in Can Tho city, Vietnamese Mekong delta

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Short description of both events with a focus on impacts

General background: Can Tho city, which is located in south west of Hau River – a branch of the Mekong River, has two seasons: a monsoonal rainy season and dry season, which occur from May to November and December to April, respectively. Flooding in Can Tho is strongly affected not only by the Mekong upstream, but also by high tide and heavy rain. In 2011, Ninh Kieu District – the core urban district in Can Tho - had 22 flooding points due to rain, 56 flooding points due to high tide (tidal peak 2.15m) and 43 flooding points due to heavy rain combined with high tide (river water level increased 80mm-1.87m)[1].

This report mentions two riverine flood events in Ninh Kieu in **27/10/2011** and **17/10/2016** during high tide period[2]. In both events, river water overflowed the edges of the Hau river and flowed into the streets through combined sewer pipes. In 2011, the highest flood event in 15 years occurred, a river water level was recorded as the highest value with 2.15m on 27th October 2011, whereas river water reached 2.03m on 17th October 2016 (Table 1, Figure 1). Both flood events exceeded the alarm III (2.0m) in Hau River. The authorities in Can Tho took some actions, such as clearing the blockage in the pipes/manholes during the time of flooding and announcing the floods to people on television. However, the warning and response actions were not clearly corresponded to each level of flood alarm. In both flood events, most streets in the centre of Ninh Kieu district were covered with up to 0.5 - 0.6 m of water during 2 – 3 hours[3,4]. According to a report of the Can Tho Drainage and Sewage Company, 38 flooded points were recorded on 17th October 2016, while flood water covered almost all main streets in Ninh Kieu district after 16:30 on 27 October 2011[5]. Since the flooding time coincided with opening/closing time of schools/offices (as show in the timeline of Figure 1), many people and vehicles were exposed to flood water. The floods affected businesses and lives of residents (Figure 2).

Table 1. Water level in flooding years in Can Tho

Flooding year	Date	The highest water level (cm)	Average Flow in Can Tho (m^3/s)	
			On day of flooding	The highest flow in month

2011	27/10	215	16,100	(05/10)19,600
2016	17/10	203	-	-

Source: Adapted from CCCO [6]

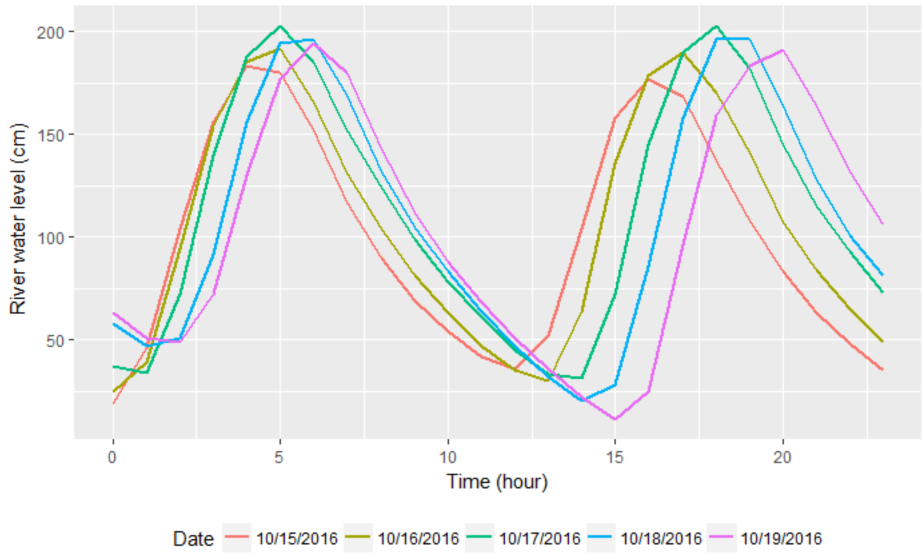

Figure 1 : Water level at Can Tho River from 15/10/2016 to 19/10/2016. Time is local (ICT). (Data source: Southern Station of Hydro-Meteorological Forecasting, Vietnam National Administration of Hydrology and Meteorology)

Flood event 27/10/2011 [3]

Flood event 17/10/2016 [4]

Figure 2. Flooded streets in Ninh Kieu district, 2011 and 2016

Descriptions of processes between events with a focus on risk management

The population in Can Tho city increased from 857 people/km² (2011) to 874 people/km² (2016). Ninh Kieu district has a higher population density than others, with 8,822 people/km². From 2004 until now, Can Tho has had three major projects that aim to develop infrastructure and reduce flooding. Urban Upgrade Project 1 (Vietnam Urban Upgrading Project) was implemented from 2004-2014. Project 1 aimed to "eliminate hunger and reduce poverty in the urban areas by upgrading/improving the living conditions and environment of the poor people living in urban areas, using planning methods with the participation of communities"[7].

In Can Tho, two outstanding works are improving Xang Thoi Lake and improving Luu Huu Phuoc Park. Xang Thoi Lake was formerly a place of "stagnant ponds and standing water", started to dredge and renovate in 2006 and be completed in 2009. Urban Upgrade Project 2 (Mekong Delta Region Urban upgrading Project) was implemented from 2012-2018 (Government Desicion 27/QĐ-TTg date 6-1-2016, Can Tho City Desicion 164/QĐ-UBND date 20-1-2016) [8,9]. Compared to Project 1, Project 2 had more focus on "improvements to environmental sanitation by rehabilitating or constructing public sewers, fostering the construction of septic tanks, providing access to septic management services, and house connections to public sewers" [7]. The outstanding works of project 2 contribute to changing the appearance of the city, such as Hung Vuong park, Bun Xang lake, and improving sewage systems. Two projects with the goal of urban embellishment, building tertiary infrastructure, alleys and low-income residential areas in suburbs of Ninh Kieu, Binh Thuy and Cai Rang and part of O Mon District[10]. The 3rd Project was started from 2016 and had been implemented before flood event 17th October 2016 - *"Urban Development and Strengthening Adaptation Project"* in order to enhance the adaptation capacity of the city with many risks, with urban flood being one of them. Comparing to two former projects, the 3rd project has more focus on reducing flood. It includes three modules: Module 1: Flood control and environmental sanitation; Module 2: Developing urban corridor; and Module 3: Strengthening Adaptation to Climate change [11]. Module 3 still continues until 2022 with total $US322 million [12,13]. The project has been implemented with the construction of a system of embankments, drains, and locks to ensure high tides; improve the existing sewer system, increase more new sewers. Besides, the ponds, lakes and canals in the area are also dredged more, to increase capacity to regulate and store water. In addition to the construction systems, the Can Tho City Development Project also has an automated system for collecting information, monitoring the water level up and down, and automatically controlling the works and operations of the sewers so that they can be promptly regulated when there are heavy rains and/or high tides. All systems will be fully automated under the management of the Can Tho City Department of Construction[14]. The infrastructure projects are summaried in Figure below.

DEVELOPMENT PARTNER ACTIVITIES:

Type	Title	Sponsor	Partners	Primary Government Counterpart	Time Period
Strategy Document	City Development Strategy for Can Tho	Cities Alliance	National Institute for Urban and Rural Planning; World Bank	Ministry of Construction	2012
Infrastructure Project	Mekong Delta Region Urban Upgrading Project	World Bank		Can Tho City People's Committee	Approved 2012
Infrastructure Project	Vietnam Urban Upgrading Project Additional Financing	World Bank		Can Tho City People's Committee	Approved 2009
Infrastructure Project	Vietnam Urban Upgrading Project	World Bank		Can Tho City People's Committee	Approved 2004

Figure 3. Some infrastructure projects in Can Tho between 2004 – 2012 (from: Can Tho, Vietnam - enhancing urban resilience)[15]

Event comparison in respect to riverine flood hazard

Recently, the issue of the water balance between the upstream and downstream parts of the Mekong River has been raised. In 2011, the river water level in Can Tho river reached 2,15m (historical flood), whilst at Chau Đoc (upstream station) the river water reached 4,25-4,9m. This means that upstream water effects urban floods downstream. In 2016, the Can Tho river water level was 2.03m, while the water level at Châu Đốc station was 2.7 m. Moreover, in 2018, river water level in Can Tho river reached 2,23m. However, the water level at Chau Đoc was 3,3-3,6m. The important issue is that the upstream water level in later years was lower, while the urban water level in the city increased. Some articles indicate that the closed dike to protect production in the upstream area has an impact on the downstream, but there is no coordinated and regulatory solution[16]. In contrast, the recent research determined that high dikes from upstream have limited impact to downstream river water levels in Can Tho[17]. On 17/10/2016, rainfall was around 30mm from 4:00AM – 6:00 AM. A 3mm/day rainfall was recorded for flood event 27/10/2011.

Event comparison in respect to exposure

All floods in 2011 caused inundation of about 27,800 houses and caused a loss of US$11.3 million including buildings, infrastructure, agriculture and aquaculture in Can Tho[18]. In addition, damage estimated for some flood scenarios with flood hazard characteristics of event 2011 was around US$3,340 thousand for private houses in Ninh Kieu [19]. The aforementioned damage estimates account for all flooded events in 2011, the damage for each event is not available.

In flood event 27/10/2011 the flood occurred around 3PM and after 1.5 hours it covered almost all main streets inner city including: Ly Tu Trong, Phan Dinh Phung, Hai Ba Trung, Hoa Binh, Mau Than, 30/4. Of these, the deepest flood water was recorded at Phan Đinh Phung, Hai Ba Trung, Nguyen Thai Hoc, Tran Van Kheo with 0.7 – 0.8m, and even nearly 1.0 m at Quang Trung street (near Dieu Hien resident area, Nam Long). The inundated area was estimated by a hydrodynamic model to be 1,174 ha.

On 17/10/2016, as Can Tho Drainage and Sewage Company have reported, there were 38 flooded streets. Flood depth ranged from 0.1 – 0.3m, flood width ranged from 1 – 16m, and flood length ranged from 15 – 500m during 0.5 – 3 hours. Most of the deepest flooded streets were located near the river and canal such as: Hai Ba Trung, Nguyen Thi Minh Khai, Quang Trung, Ly Hong Thanh [20]. The inundated streets covered an area of 64,037 m^2 (Can Tho water supply company)

Event comparison in respect to vulnerability

People built dykes with sandbags to prevent floods coming into the houses or put water pumps to pump out water [21]. Can Tho has a Steering Committee for Disaster Preparedness and Search and Rescue (SCDPSAR). However, information was not successfully announced to local people for early warning during the flood [22]. Local people usually use sandbag dikes at home to prevent water entering, and pump at home to pump out water.

In general, business loss, vehicle damages, and house degradation were reported in these two events. Intangible impacts recorded for the 2016 are polluted flood waters and human health risk related to waterborne pathogens in flood water [23,24].

Summary

The flood event on 27/10/2011 happened during high tide period and was identified as the highest flood event in 15 years. During the flood, almost the entire inner city was flooded. At that time, it was reported that there was lack of efficient solutions for flooding issues in Can Tho [25]. In 2016, Can Tho had more solutions to reduce flooding after finishing Project 1 and part of Project 2 [26]. With the project 1 and a part of project 2, more canals, drainage, and sewage pipes were renovated to increase the capacity that helped to reduce the flood. However, the event occured on 17/10/2016, combined with flood high tide (lower magnitude than the 2011 event), and rainfall also led to severe flooding. Whilst flooding is a very serious issue in Can Tho city, there is limited information regarding damage assessment. inundated area was significantly smaller than in 2011, e.g. 64,037 m² of flooded streets (Can Tho Drainage and Sewage Company, 2017)

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SUPPLEMENTARY

(a)

(b)

(a) Flood on Huynh Cuong street in the evening (18:15), which was caused by very high tide (17th October 2016). Surface water exceeded the bank of Xang Thoi lake (on the left hand in picture) and the pavement which had some motorbikes parked on it. Flood water on teh street was the combination of surface water and sewer water on sewage system. (Photo by Huynh Thi Thao Nguyen)

(b) Flood on Chau Van Liem street on morning (7:00) which was caused by high tide and heavy rainfall from early morning (17th October 2016) (Photo by Huynh Thi Thao Nguyen)

ID 33

Paired drought events: December 2000 to December 2002 and February 2007 to May 2009 droughts in the State of North Carolina in the United States of America

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Short description of both events with a focus on impacts

In the last 20 year period, the State of North Carolina has had two intense drought periods: December 2000 to December 2002 and February 2007 to May 2009 (National Drought Mitigation Center (NDMC) 2020c). The main two impacts for both of these droughts are quantified through agricultural losses and enacted water restrictions for municipalities within the state. During the 2000-2002 drought, crop losses were estimated at 576 million dollars (CPI adjusted for US Dollars in 2020), while almost 250 of the 552 municipalities in the state employed water restrictions (United States Geological Survey (USGS) 2005; North Carolina League of Municipalities (NCLM) 2020). Unfortunately, the impacts of the 2007-2009 drought were even worse, with about 610 million dollars in agricultural losses (CPI adjusted for US Dollars in 2020) and 292 municipalities operating under some form of water restrictions (North Carolina Department of the Environment and Natural Resources (NC DENR) 2009).

Descriptions of processes between events with a focus on risk management

After the 2000-2002 drought event (but before the 2007-2009 event) North Carolina made two policy changes to increase risk management. First, the then current drought task force, called the "North Carolina Drought Monitoring Council" was renamed the "North Carolina Drought Management Advisory Council (NC DMAC)" by North Carolina's General Assembly (legislature) in 2003. The General Assembly also gave the NC DMAC the authority to issue drought advisories and continually conduct localized drought assessment. Second, in 2005, North Carolina released its "Drought Assessment and Response Plan" that works in conjunction with the State's Emergency Operation Plan. This plan gives authority to specific state agencies on how to respond and manage drought conditions to reduce impacts to water supplies and agriculture (NC General Assembly 2007). These two efforts were set up to help coordinate drought response efforts during the next event to minimize potential impacts (NC DMAC 2020a).

Event comparison in respect to drought hazard

In general, most of the water resources in North Carolina originate from precipitation falling within the state, while some water does flow into North Carolina from neighboring states (NC Climate Office 2020). Therefore, drought in North Carolina usually stem from meteorological droughts and cascade into agricultural, hydrological, socioeconomic, and/or ecological drought if the meteorological drought conditions last for a long enough period (USGS 2005). This is the case for both the 2000-2002 and 2007-2008 drought events, where long enough periods of deficient rainfall turned into agricultural, hydrological, and socioeconomic droughts. The NDMC's product, the United States Drought Monitor (USDM), is a composite drought indicator that uses a blend of meteorological, soil moisture, hydrological, and other indices to calculate drought severity for a given location using percentile rankings (NDCM 2020d; World

Meteorological Organization (WMO) 2016). With these percentile rankings, the USDM provides 5 categories, abnormally dry (D0), moderate drought (D1), severe drought (D2), extreme drought (D3), and exceptional drought (D4), with D0 being the least severe and D4 being the most severe (USDM). The Category of D0, abnormally dry conditions, are not actually considered drought conditions but serve as a potential indicator for an area that may be facing emerging drought conditions or coming out of a drought period.

Accounting for only drought categories (D1-D4) for these two drought periods, the 2000-2002 and 2007-2009 drought events differed from one another. Figure 1 shows the amount of time and percentage of the State of North Carolina spent in each drought category from January of 2000 to January of 2010. During the 2000-2002 drought event the state fluctuated between different amounts of area in different drought severity classifications. During this drought event, the most severe period came at the end, between December 2001 and December 2002, with most of the state was in a severe drought (D2) or more (D3 or D4) and peaking at maximum drought intensity in August of 2002. During the 2007-2009 drought event, the drought intensity ramped up quickly, where much of the state was in extreme drought (D3) or higher (D4) between September 2007 and March 2008, with the peak of the drought occurring in December of 2007. From this point onward, the drought severity and spatial extent fluctuated over the state, but generally tapered off until full abatement in 2009.These two events differed from one another because the 2000-2002 drought fluctuated over time and reached maximum intensification towards the end of the event, while the 2007-2009 drought intensified very quickly, and then fluctuated over time until the end of the event.

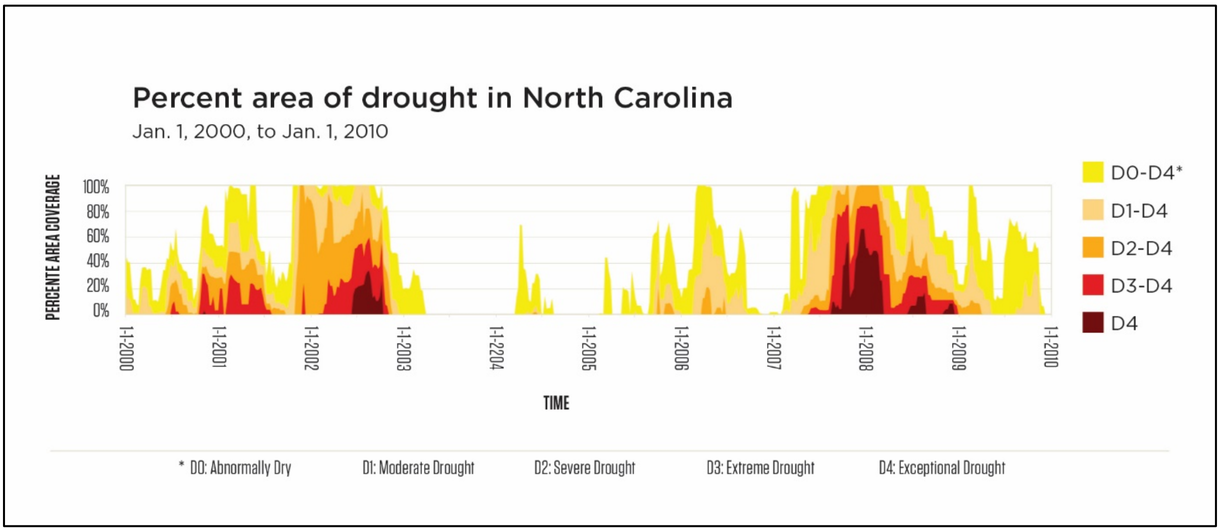

Figure 1. USDM drought time series from 2000 to 2010 (NDMC 20120c).

Event comparison in respect to exposure

Figure 2 shows the peak drought intensity during the 2000-2002 event, while Figure 3 shows the peak drought intensity during the 2007-2009 event. Figures 2 and 3 provide the differences in spatial extent for the peak drought intensity of both events, showing that the peak intensity of the 2007-2009 drought event covered more area than that of the 2000-2002 event. Table 1 shows the percent area, the number of counties, and the total population that was affected by each category of drought during the peak intensity for these two events. Comparing these two figures and the data provided in Table 1, it is clear that the 2007-2009 drought event was much more severe than the 2000-2002 event based upon the amount of area and people affected by each drought severity category during the peak intensification of the drought.

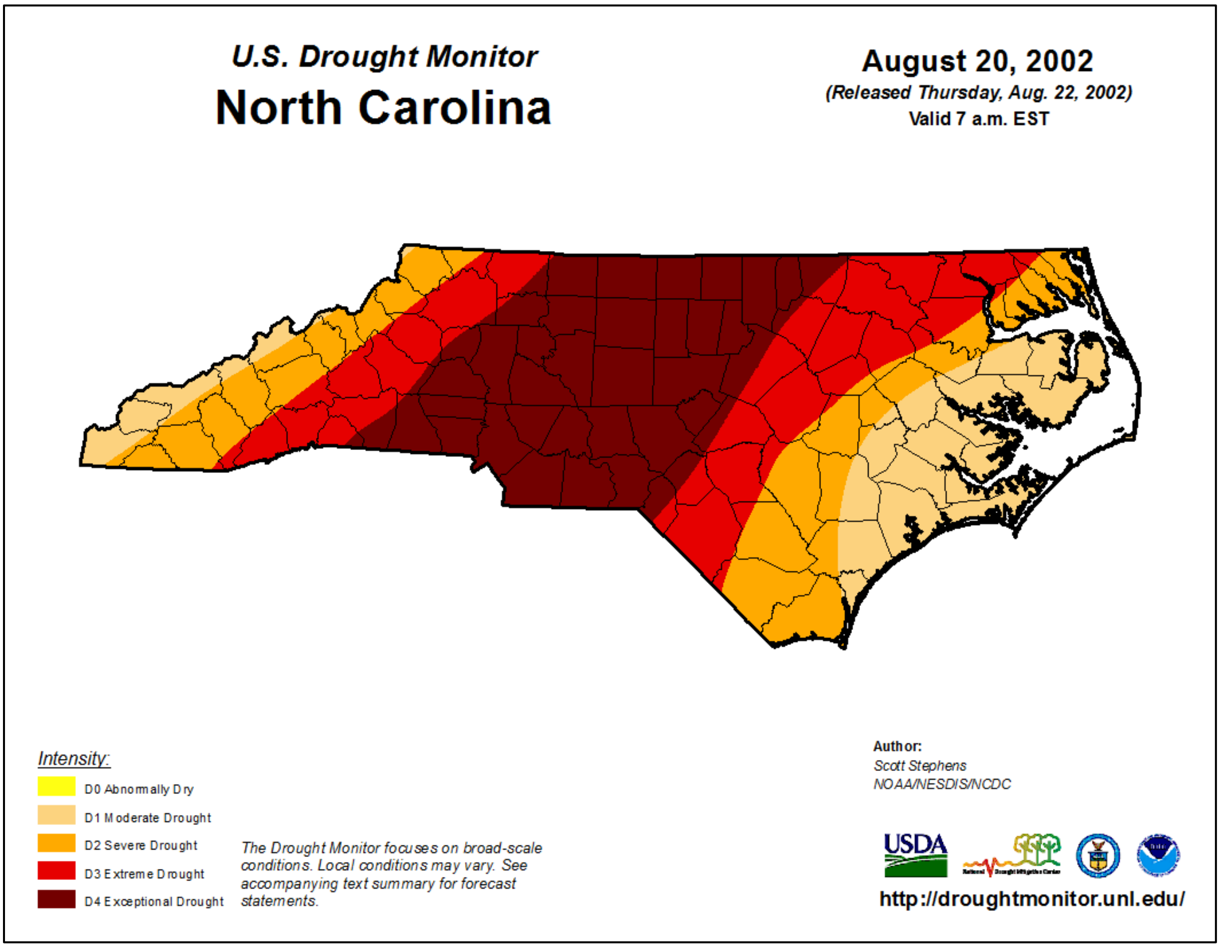

Figure 2: Peak drought intensity spatial extent during the 2000-2002 drought event (NDMC 2020a).

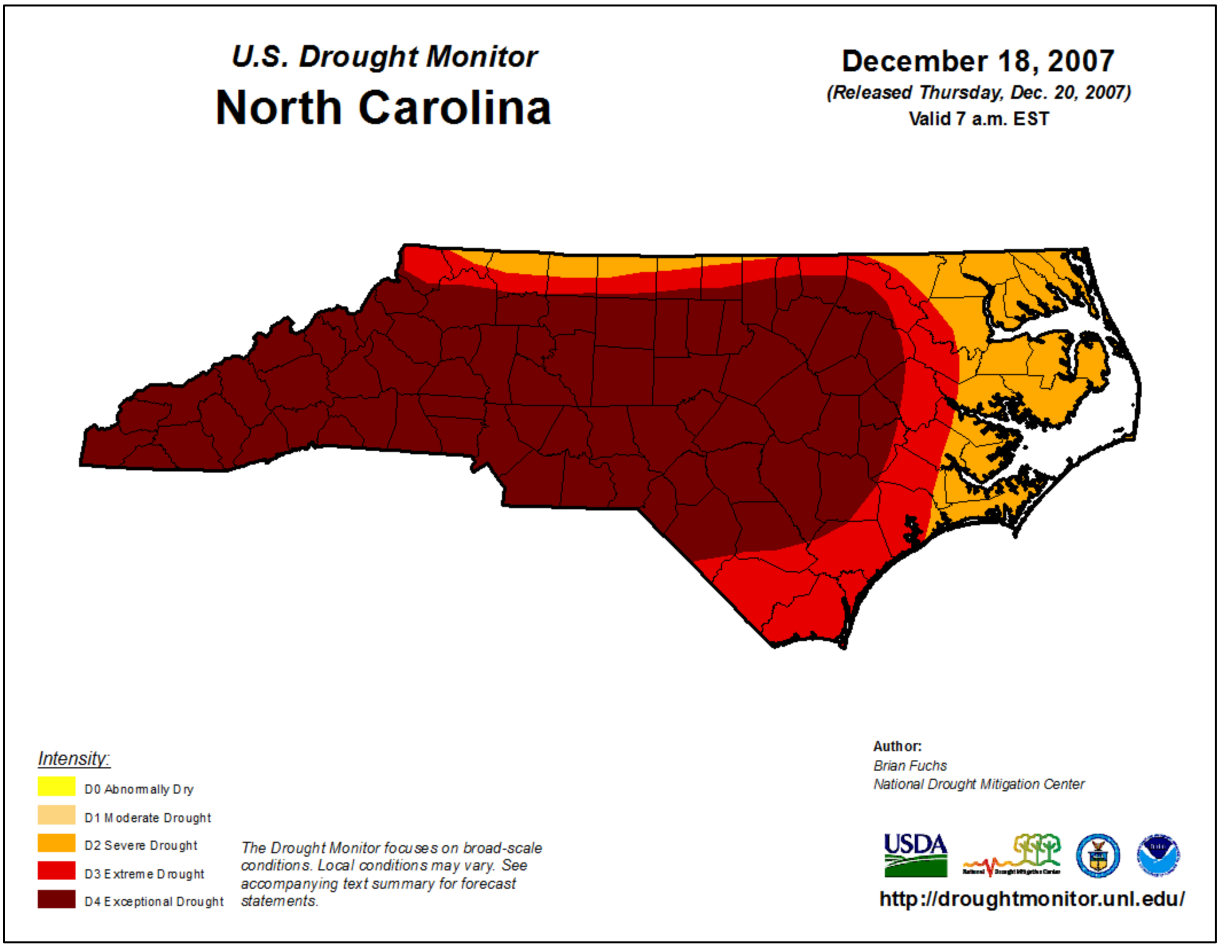

Figure 3: Peak drought intensity spatial extent during the 2007-2009 drought event (NDMC 2020a).

Table 1: Spatial extent and the amount of people affected during peak intensity for both drought events (NDMC 2020b; NC DMAC 2020b).

Drought Event: 2000-2002			
USDM Category	Percent Area	Number of Counties[1]	Population
D1	18.14%	14	9,522,025
D2	22.30%	25	8,572,038
D3	25.73	23	7,457,049
D4	33.83%	38	5,219,377
Drought Event: 2007-2009			
USDM Category	Percent Area	Number of Counties	Population
D1	0.00%	0[2]	9,522,025
D2	15.96%	14	9,522,016
D3	17.84%	15	8,978,495
D4	66.20%	71	7,888,657

[1] There are 100 counties in the State of North Carolina. During the 2000-2002 event, all 100 counties were in some category of drought severity

[2] During the peak intensity of the 2007-2009 drought event, all of the counties in North Carolina were in a D2 category or higher, resulting in zero counties being in the D1 category.

Event comparison in respect to vulnerability

Vulnerabilities changed between events due to two factors. First, management practices that were implemented after the first event to help reduce vulnerability. The severity of this drought demonstrated that the State of North Carolina needed stronger drought management in place to deal with severe droughts in the future. Thus, in 2003 the North Carolina Drought Monitoring Council was upgraded to the NC Drought Management Council to enhance drought early warning and management during the onset and through the duration of a drought period (NC DMAC 2020a). In addition, the State of North Carolina implemented a state-level drought response plan in 2005 that worked towards reducing drought impacts during a drought event. The increase in drought management, particularly in response measures, helped reduce drought vulnerability and alleviate impacts during the next drought event (2007-2009). Secondly, vulnerability to the second drought event actually increased despite the recently increased drought management actions because the 2007-2009 drought event was the worst drought on record (NC DMAC 2009). The agricultural losses were higher and the amount of local water restrictions enacted were higher in the 2007-2009 drought compared to the 2000-2002 drought event (USGS 2005; NC DENR 2009). Although the State of North Carolina took action to reduce vulnerability after the 2000-2002 drought event, the severity of the 2007-2009 event severely challenged these efforts. This results in both an decrease and increase in vulnerability, where vulnerability decreased from an increase of drought management, while vulnerability increased during the 2007-2009 drought period due to its extreme intensity and severity.

Summary

Within a decade, the State of North Carolina went through two major drought periods: 2000-2002 and 2007-2009. Both of these events caused over 300 million dollars in agricultural losses (both over 500 million dollars based on CPI adjusted inflation for 2020), over 200 hundred municipalities within the state under water restrictions, and over 5 million people affected from these impacts (USGS 2005; NC DENR 2009). The 2000-2002 drought lasted about 24 months and with intensity slowly building over time and peaking towards the end of the event in August of 2002 (Figure 2), where NDMC 2020 over 75% of the state was in severe drought (D2), over 50% was in extreme drought (D3), and over 30% was in exceptional drought (D4) (Table 1) (NDMC 2020a; 2020c). Just five years later, North Carolina found itself within another intense drought event (2007-2009), which turned out to be the worst drought on record (NC DENR 2009). This drought lasted for about 27 months and the intensity of this drought developed quickly and peaked in December 2007 (Figure 3) where 100% of the state was in severe drought (D2), over 80% was in extreme drought (D3) and over 65% was in exceptional drought (D4) (Table 1) (NDMC 2020a; 2020c).

As evident by the drought policy changes that North Carolina has enacted, the State has worked to reduce drought vulnerability after each drought event through increasing management actions. After the 2000-2002 drought, the state increased early warning and management by creating the North Carolina Drought Management Council and creating a state-wide drought response plan to reduce future drought vulnerability. However, the 2007-2009 drought event was so intense and severe that it challenged the capabilities of the newly established drought management practices. Thus, during the 2007-2009 drought event, the North Carolina General Assembly required all local water supplies and municipalities to create water shortage response plans, so that drought response measures would better fit individual and unique drought management needs at the local level (North Carolina General Assembly 2007). Although North Carolina has increased its early warning and response management to drought periods, it has yet to work towards drought mitigation efforts at the state level. Perhaps the next severe drought period will shift North Carolina's drought management from a response approach (crisis management) to mitigation approach (risk management) to reduce future vulnerability and impacts.

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ID 34

Paired drought events: 1986-1989 and 2004-2008 droughts in Catalonia

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Short description of both events with a focus on impacts

The two meteorological drought episodes analyzed here affected Catalonia (NE Spain), and extended to much of the North of the Iberian Peninsula. The precipitation deficiency was combined during the summer months with some heat waves that increased potential evapotranspiration. In the Mediterranean climate regime, rainfall deficit situations are frequent (Figs. 1 and 2), among which are deficits 1986-1989, and 2004-2008, which will be studied here.

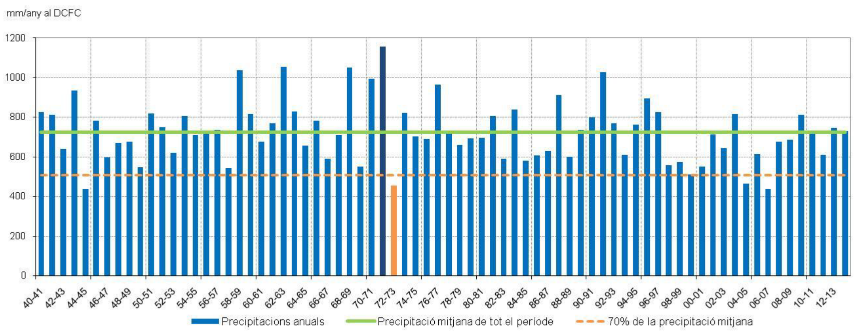

Figure 1. Evolution of the average rainfall in the River Basin District of Catalonia (DCFC) from the hydrological year 1940-1941 (from September to October) to the hydrological year 2013-2014. Source: Agència Catalana de l'Aigua (ACA).

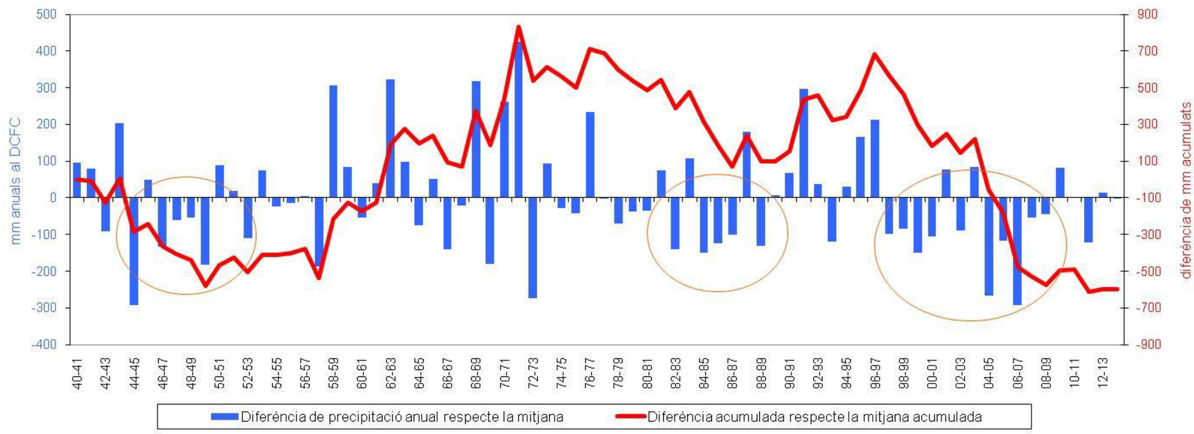

Figure 2. Evolution of the annual average precipitation anomalies in the River Basin District of Catalonia (DCFC) from the hydrological year 1940-1941 (from September to October) to the hydrological year 2013-2014. Source: Agència Catalana de l'Aigua (ACA).

In particular, they affected the Ter-Llobregat system (Fig. 3) constituted by the Llobregat River and the Ter River, and the Segre River, which essentially feed on the rainfalls that fall in the basin (mainly in the Pyrenees Mountain). The existing reservoirs in those rivers are key in the distribution of water resources in Catalonia, for the following reasons: 1) they provide water to a large number of cities, including Barcelona and Girona, where most of the population is concentrated; 2) they provide irrigation water for agriculture; 3) they provide hydroelectric power; 4) they are used as a flood prevention system; 5) they must maintain ecological discharges. It is therefore an example of multipurpose dams (flood control, hydropower, ecological discharges, water supply, irrigation). In drought situations, these different objectives may be in conflict (Labadie, 2004; Dittmann et al., 2009; Bianucci et al., 2015). Tables 1 and 2 show the main characteristics of both rivers and their reservoirs.

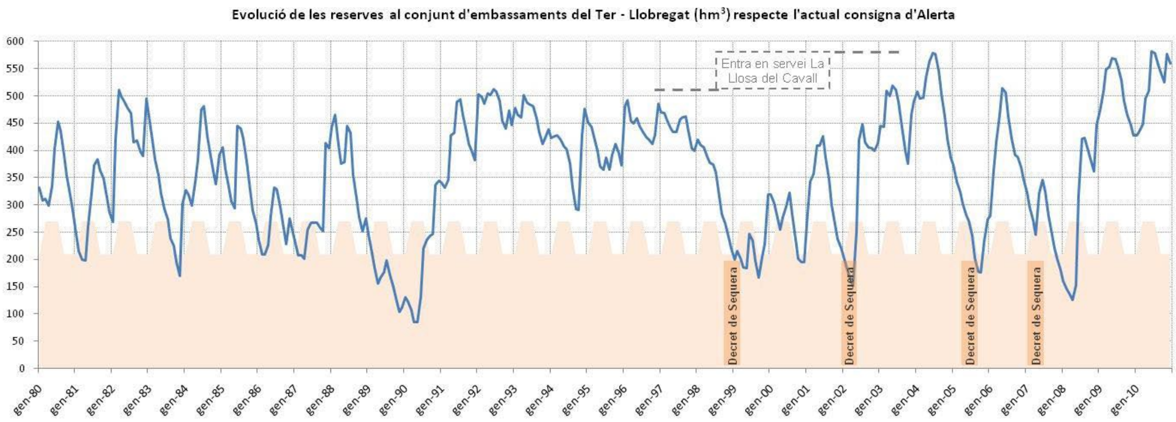

Figure 3. Historical evolution of the reserves of the set of reservoirs of the Ter-Llobregat system, in which the promulgation of Drought Decrees from 1999 stands out. Source: Agència Catalana de l'Aigua (ACA).

River	Length (km)	Mean flow (m^3/s)	Surface (km^2)
Ter	208	25	3010,5
Llobregat	170	19	4948
Segre	265	100,2	22579
Muga	58	3,34	853,8

Table 1. Main features of Ter River, Llobregat River, Segre River and Muga River

Dams	Capacity (hm3)	Surface (ha)	Catchment area (km2)	Year		Energy (Million Kw.h)
Sau (Ter)	151	573	1522	1962	I/D/E/F	85
Susqueda (Ter)	233	466	1775	1968	I/D/E/F	180
Pasteral (Ter)	2	35	23	1905	I/E/F	31
Colomers (Ter)	1	70	-	1970	I	-
La Baells (Llobregat)	115	365	532	1976	I/E/D	23
Llosa del Cavall (Llobregat)	79,4	300	200	1989	I/E/D	-

Graus (Tavescan)	0,33	5		1973	I/E/D	
Tavescan (Noguera de Cardós)	0,64	7,9		1966	I/E/D	
Oliana (Segre)	101,1	443		1959	I/E/D	57
Rialb (Segre)	402,8	1505		2000	I/E/D	217
San Lorenzo Mongai (Segre)	9,51	131		1930	I/E	4
Terradets (Noguera-Pallaresa- Segre)	33,19	330		1935	I/E	
Camarasa (Noguera Pallaresa-Segre)	163,4	624		1920	I/E	
Tremp (Noguera Pallaresa)	205,1	926,6		1916	I/E	
Canelles (Noguera Ribagorzana)	678	1569		1960	I/E	
Escales (Noguera Ribagorzana)	152,37	432		1955	I/E	
Santa Ana (Noguera Ribagorzana)	236,6	767,85		1964	I/E	
Ribarroja (Tarragona)	209,6	2028,9		1969	E	
Cavallers (Noguera de Tor-Segre)	15,77	47,27		1960	E	
Capdella	50	-			E/D	
Certescans (Noguera de Cardós-Segre)	15,6	61,2		1944	E	
Aiguamoix (Lleida)	1	9		1969	E	
Alos (Lleida)		29		1991	E	
Amitges de Ratera (Lleida)	1	8		1958	E	
Balaguer (Segre)	1	42		1958	E	
Boren (Lleida)	0,8	11,2		1958	E	
Cardet (Leida)		14		1953	E	
Estany Gento (Flamisell)	3	28		1914	E	
Fosse (Flamisell)	5,3			1915	E	
La Torrassa (Noguera Pallaresa)	2,1	48,7		1941	E	
Reguera (Lleida)	1	10		1942	E	

Restanca (Lleida)	1	7		1955	E	
Rumedo Inferior (Flamisell)	1	10		1971	E	
Saburo (Flamisell)	11	28		1934	E	
Salado (Flamisell)	1	9		1931	E	
Sallente (Flamisell)	6,48	28,6		1985	E	
Sant Maurici	2	25		1975	E	
Sistema Valle de Arán (Vallarties)	23				E	
Utchesa	4	74		1915	I	
Utchesa Seca	4	120		1915	I	
Utchesa Valleta	4	48		1915	I	
Guiamets (Tarragona)	9,7	72		1975	I	
La Palma d'Ebre	1	19		2001	I/D	
Boadella (Muga)	60,2	363,3		1969	I/D/F/E	
Siurana	12,43			1972	I/D	
Foix	1	79		1937	I	

Table 2. Main features of dams built in the Ter River, Llobregat River, Segre River and Muga River. Last column shows the average annual energy produced in the hydroelectrical central associated to the dam or reservoir. E: energy; I: irrigation; D: drinking water; F:flood prevention Source: https://es.wikipedia.org/wiki/Anexo:Embalses_de_la_cuenca_del_Ebro, different web pages, CHE, ACA

1986/87-1989/90: This period of 4 years was characterized by long dry spells (until four months without precipitation), with heat waves. As a consequence of the two dry consecutive years 1988-1989, the reservoirs of Ter-Llobregat System achieved absolute minimum reserves, a situation that was especially delicate because the most affected was the Ter band, when it usually offers the largest and most regular contribution. This drought led to reservoirs at critical levels, overall worse than in 2008, although it was climatically less severe. But its effects were more serious because the Llosa del Cavall reservoir still did not exist and, above all, because the lower perception of the risks of disaster allowed a high priority to hydroelectric discharges, which would be unthinkable today. There were about to make restrictions on the water service in Barcelona, which means that the maximum alert level was reached, although at that time there was still no drought management plan. Finally, no restrictions were applied to the Barcelona city in the end because there were widespread rains throughout the region in October 1990. The most important impacts in 1989 due to the drought were severe losses in the agriculture, mainly in cereal crops, lack of drinking water due to water salinization or no water supply (more than 40 municipalities suffered severe restrictions in August), economic losses in ski resorts due to lack of snow (losses of more than 5000 million ptas. -67.193.153,3 €$_{2019}$- in the winter tourism sector), and losses in hydraulic production. The drought also affected the rest of Spain, where the losses in the hydroelectric sector due to the drought between October 1988 and January 1989 were 35000 million ptas. (503.948.649 €$_{2019}$) and between 20 and 25% of cereal production was lost. As a result of water scarcity and the increase in electricity consumption, there was an increase in imports of oil and coal. Besides the hydrological impacts, there were more than 350 forest fires and 45000 ha burned in Catalonia in 1986, being the severest one the case produced in the Montserrat Mountain, where several people died and more than 41% of the protected Natural Park was destroyed (Turco et al, 2013). Winter forest fires were also produced in Catalonia in 1986, fact that is unusual. The experience of those critical moments it allowed to learn many lessons that have been applied in the drought management and forest fire prevention of the following years.

2004/05-2007/08. Drought resulted in very significant economic losses in the primary sector. In agricultural activities, drought affected both dry land and irrigated crops. In the first ones due to the absence of precipitation and, in the second, due to the lack of water in reservoirs. Cereals in the Lleida regions were the first damaged crops, with losses, in some cases, of 100% of the harvest. The nut crops, the olive and the vine were affected by the insufficiency of rains, both in the regions of Tarragona and Lleida. The network of irrigation channels in the western regions adopted different strategies to dose the water supply. For example, the Community of “Regants del Canal d’Urgell” closed in spring the channel for some days to prolong the irrigation season. The adoption of all these extreme measures caused the production of irrigated crops to decrease significantly. In July 2005, the Department of Agricultural Livestock and Fisheries (DARP) estimated that agricultural production in 2005 would decrease by 7%. According to the same source, the counties of Bages, El Solsonès, Osona, El Gironès, La Segarra, L'Urgell, El Segrià, El Pallars Jussà and Anoia (Pre-Pyrenees and Lleida), in July, were the most affected.

The lack of water to breed livestock in the counties of the Pre-Pyrenees and Lleida led to the transport of water in tanker trucks. This fact greatly pushed the costs of exploitation of livestock. The most harmed sectors were sheep and goats. In the Pyrenean area, summer transhumance had to be done through the Vall d’Aran, the region less affected by drought. In the rest of the Pyrenees, the pastures were very dry. The deficit of precipitation also affected forests and resulted, on the one hand, at a high risk of fire and, on the other, in the drying of many trees due to water stress, and the reduction of forestry production.

As the year 2005 progressed, water reserves of reservoirs and aquifers gradually decreased. On the month of May more than seventy population centers of twenty-two municipalities in the counties of Lleida had water supply restrictions (including water for agriculture, livestock’s and also for human consumption). Paradoxically, the most affected regions were Alta Ribagorça, Pallars Jussà and Alt Urgell (Pre-Pyrenees), that is, demarcations where usually precipitation is high. In the first week of June, drought already affected 95% of the municipalities of Catalonia. In the summer the reserves continued to decline. The reservoirs of the Ter and Llobregat basins, which supply water to the counties of Barcelona and Girona, were below 45% of their capacity. If in June 2004, the water stored in the Llobregat-Ter dams was near 600 hm^3, in June 2005 it was less than 290 hm^3 arriving at a minimum in October 2005 of less than 200 hm^3, into the warning level that lasted until December 2005. The total dam volume in the Llobregat-Ter system never returned to the initial values of 2003, despite some heavy rainfall events. Autumn rains relieved drought. The return of rainfall in autumn 2005 (mainly in the coast) avoided restricting supply for domestic use in more than half of the population of Catalonia, but in November there were still sixty populations with restrictions. The reservoirs, at the end of November, stood at 47% of their capacity. In August 2007 the warning level was reached again and this maintained until June 2008, arriving in April 2008 at the emergency level with less than 150 hm^3 stored in the dams of the Llobregat-Ter system that seriously threatened the supply of drinking water in Barcelona and Girona. On 1 April

2008, total water stored in Catalonia was of 125 hm^3 (near the 20% of the maximum capacity).

Descriptions of processes between events with a focus on risk management

No water awareness campaigns during the 1986-1989 event. Important campaign during the 2004-2008 event.

After the 1986-1989 drought period the reservoirs of La Llosa del Cavall (79,4 hm^3), Rialb (402,8 hm^3) and la Palma d'Ebre (1 hm^3) were built to supply drinking water and water for irrigation, as well as the construction of the mini-transfer from the Ebro River to Tarragona. This helped the management of the drought 2004-2008. Because of the 2004-2005 drought a desalinization plant was built in Barcelona and 200 water wells (mainly urban) were recuperated to use their groundwater to supply the necessities of the System. In 2003-2004 the urban water supplied by the water wells was 35 hm^3/year and this quantity increased in 2007-2008 to 65 hm^3/year. The average annual water demanded for irrigation in the Baix Ter was approximately 111 hm^3/year (76 hm^3/year from dams and 35 hm^3 from tributaries nonregulated). In 2008 the total water consumption by irrigation was near 90hm^3 (less than 60 hm^3 was provided by dams).

Forest fire prevention and extinction were improved a lot after the forest fires that affected Catalonia on 1986, 1994 and 2003, with the elaboration of the INFOCAT planning. Consequently, no major forest fires were produced because of the drought and heat waves that affected Catalonia between 2004 and 2008, in spite the increase of forest mass (Turco et al, 2013).

It is important to have in mind that farmers usually meet in April with the Commission that decide the water supply from reservoirs for the irrigation campaign, in order to decide the crops that should be planted that year based on the probabilities of the available water volume. If in this moment reserves are above 367 hm^3 it is very likely that the campaign will develop normally. Forecasts are based on climate values. In neither case analyzed here were seasonal forecasts considered.

Event comparison in respect to drought hazard

Drought will be related to water scarcity due to a negative anomaly of precipitation, and the Standard Precipitation Index (SPI) will be used as indicator. From an operative point of view by the Water Agencies, the use of SPI as drought indicator is more spread than the use of SPIE (Vicente-Serrano et al, 2010), that, on the contrary, is better for climate change and seasonal forecasting studies (i.e.Turco et al, 2018a, 2018b). In this study two sources of rainfall information have been used. The first one (Llasat et al, 2009) has obtained the SPI-12 index (McKee et al. 1993) in basis to more than 850 stations in Catalonia with monthly rainfall data provided by the Spanish National Meteorological Institute (INM, currently the State Agency of Meteorology, AEMET) and the Catalan Meteorological Service (SMC), for the period 1948–2007. A grid of 0.02×0.02 degrees has been built for this period, using the kriging methodology. Once a SPI series (1982–2006) had been obtained for each pixel, the average value was calculated for the entire region. Based on the SPI values it was possible to distinguish seven types of situations (Lloyd-Hughes and Saunders, 2002), from wettest to driest. This analysis has allowed to distinguish the period 1986-1989 with average negative SPI-12 values in 1986, 1987 and 1989, and the period 2004-2008 with a minimum near -1.5 in 2005.

The second source is provided by the SAFRAN analysis (Quintana-Seguí et al., 2016, 2017), used to compute the spatial distribution along the entire Iberian Peninsula of SPI-3, SPI-6, SPI-12, and the SURFEX LSM, forced by SAFRAN, in order to compute the standardized soil moisture index (SSMI) for the root zone layer with a scale of 1 month (SSMI2-1). SPI and SSMI were computed by means of the non-parametric method by Farahmand and Aghakouchak (2015). SPI-3 was selected for determining the starting and end month of the meteorological drought, following Turco et al. (2017) who obtained a good correlation between burned area in Mediterranean eco-regions and SPI-3, and Coll et al. (2016) that used SPI-3 to identify meteorological droughts in Barcelona for a period of more than 200 years. In the present contribution, a minimum of four consecutive months with SPI-3<0 will be required. However, the drought in the soil can last longer than the meteorological drought. For the drought intensity minimum values for SPI-12 and SSMI2-1 are selected. We have used the definition of AEMET for heat wave: ”Heat wave is an episode of at least three consecutive days, in which at least 10% of the stations considered record maxima above the 95% percentile of their series of maximum daily temperatures of the months of July and August from the period 1971-2000” (AEMET, 2017)

1985/86-1989/90. Although in 1986 any heat wave was not recorded, the months of July and August recorded strong negative anomalies of SPI-12 and SSMI2.1 (less than <-3) in the major part of the Iberian Peninsula. There were numerous forest fires that were particularly damaging in Catalonia. On August and September 1987, two heat waves of 6 days were recorded in Spain, that affected, respectively, 13 and 27 provinces. However, the driest months in the major part of Spain were May and June of 1987, and only in the case of the Catalonia, it was a coincidence between a heat wave and negative SPI-12 values on August. On October 1987 a catastrophic flood event, affected Catalonia and Valencia (Eastern part of Spain), with more than 400 mm and 700 mm in less than 5 days, respectively. SPI and SSMI recovered positive values until September 1988 when SPI-3 was <-3 in a great part of the Peninsula, mainly in Catalonia were SSMI2-1 recorded values <-3. A short heatwave was recorded in Spain in September 1988 (23 provinces). Despite the heavy rains produced in November 1988 in Catalonia, the precipitation deficit and soil humidity were not recovered and negative values of SPI-12 and SSMI2.1 dominated in Catalonia until November 1989. The situation was worsened because of two heat waves recorded in July 1989, lasting 6 days the first one and affecting 36 provinces.

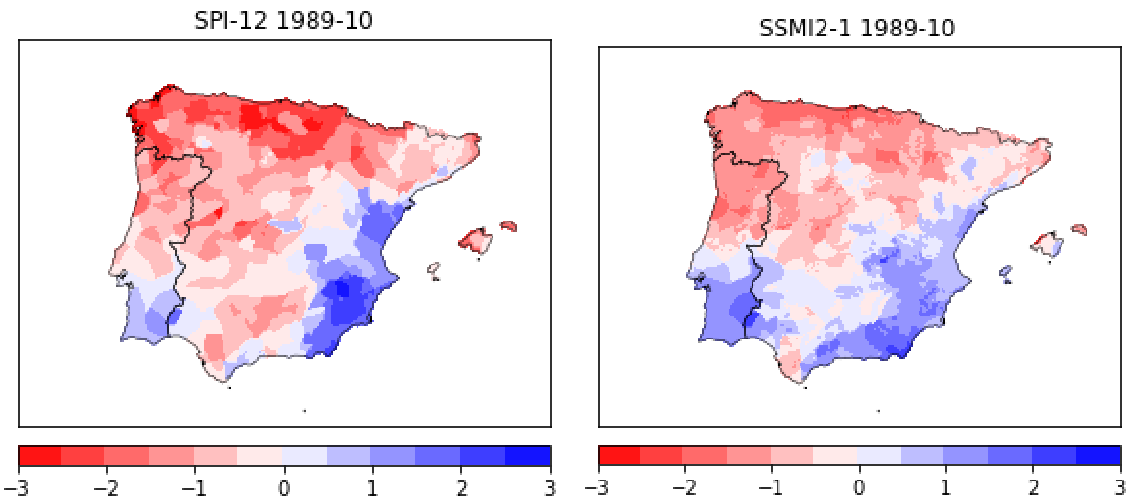

Figure 4. SPI-12 and SSMI2-1 in October 1989 in Spain and Portugal (left: SAFRAN reanalysis; right: SURFEX LSM forced by SAFRAN).

2003/04-2007/08. After the heat wave that affected Europe in 2003, a rainy period was recorded in the East of Spain until June 2004. June and July 2004 recorded two short heat waves that lasted three days each. Negative values of SPI-1 and SPI-3 were recorded in some zones of this region in August 2004 and this precipitation deficit lasted until August 2005 (the deficit affected the entire Iberian Peninsula during 2005). In spring and summer 2005, the drought affected the major part of the Iberian Peninsula, and values of SPI-12 and SSMI2.1 <-2 were recorded until October 2005 in Catalonia, where two flood events affected this region in October and November 2005. However, the negative values of SPI-12 were extended until summer 2006 in the East of Spain. Two heat waves of 4 days each were recorded in some regions of Spain in July and August 2005 and two more of three days in July and September 2006. A consecutive meteorological drought event started in Catalonia in April 2006 and lasted until August 2006 and started again in November 2006 and lasted until April 2007, if we consider the values of SPI-3. But if we consider SPI-12 it could be considered as the same drought event in the Northern part of Catalonia, on the Pyrenees, where the major part of its rivers is born. After a wet spring, negative values of SPI-3 were recorded in the North-Eastern part of Spain from July 2007 until May 2008 and negative values of SSMI2.1 corroborated a dry soil in all the Iberian Peninsula, except for Valencia Region (Eastern part, south of Catalonia). A short heat wave (4 days) was recorded in July 2007.

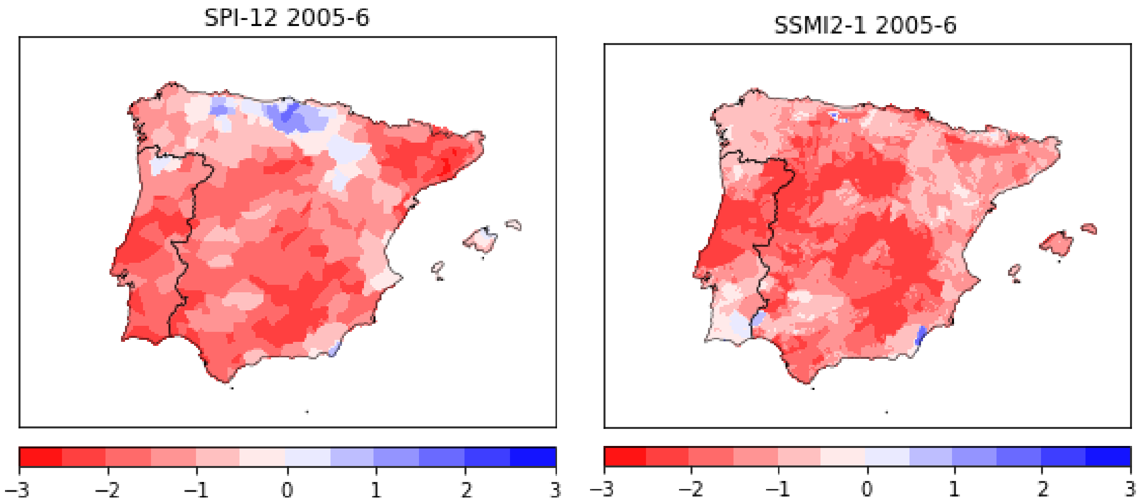

Figure 5. SPI-12 and SSMI2-1 in June 2005 in Spain and Portugal (left: SAFRAN reanalysis; right: SURFEX LSM forced by SAFRAN).

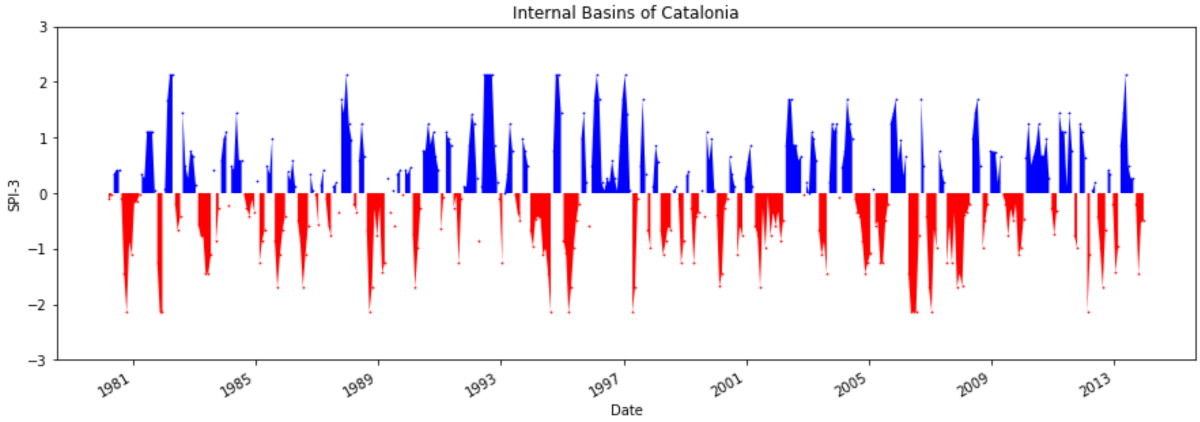

Figure 6. Evolution of average value of SPI-3 for the Internal Basins of Catalonia (SAFRAN reanalysis).

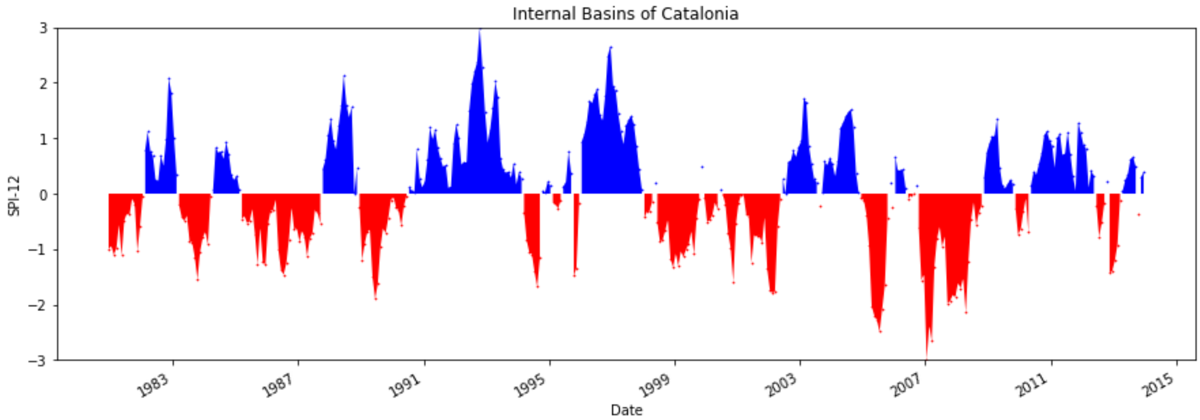

Figure 7. Evolution of average value of SPI-12 for the Internal Basins of Catalonia (SAFRAN reanalysis).

Figures 6 and 7 allows comparing both drought events. In both cases average regional values of SPI-3 arrived to -2 although it was more frequent in the 2004-2008 event. However, SPI-12 reveals that this second event was more intense than the previous one, with minimum values near -3 and a major number of months with values less than -1. In spite that some positive values of SPI-3 and SPI-12 appear during the drought event, associated rainfalls were not enough to solve the water scarcity in the region.

Event comparison in respect to exposure

Due to the great extension of both drought events the people exposed to them was all the population in Catalonia, that increased from 6.125.339 people in 1989 to 7.298.313 people in 2008. To this population it is needed to add tourism: in 2008 the number of foreigners' tourists in Catalonia was of 15.026.900; in 1989 this quantity was below 9.000.000. In both cases Barcelona was the hotspot city, due to the great concentration of population: 1.712.350 inhabitants in 1989, 1.615.908 inhabitants in 2008. In spite to this population decrease in Barcelona city due to the increase in the price of housing, the population in the Metropolitan Area of Barcelona has increased from 3048479 inhabitants in 1991 to 3220476 inhabitants in 2011. Although since 2013 the population is also decreasing in the Metropolitan Area of

Barcelona due to gentrification, the water consumption is not decreasing due to the strong touristic development and associated services.

Because of the great rainfall variability (inter-annual and intra-annual) water storage is fundamental for irrigation, drinking water (mainly in Barcelona and Metropolitan Area of Barcelona that is mainly supplied by the Ter-Llobregat system), hydroelectric power production (approximately 3900 GWh per year). Some dams have been also built for flood management. After the 1986-1989 drought three more reservoirs were built (La Llosa de Cavall, Rialb and La Palma d'Ebre) to guarantee drinking water and irrigation.

Although the extension of irrigated crops had increased a little in Catalonia between 1989 and 2004, the most significative changes will be produced in the next years. The Irrigation Plan proposes a notable expansion of the irrigated area, from little more than 300,000 ha. in 2008 to 439.016 ha. in 2020

Event comparison in respect to vulnerability

The preparedness in front forest fires, that are favoured by dry periods, constitute a good practices example, due to the improvement of people awareness (trough sensibilization campaigns and new normative), forecasting (nowcasting, short-term forecasting and seasonal forecasting) and extinction measures (Turco et al., 2013, 2019). As example, between September 2003 and September 2008 maximum annual burned areas were less than 10000 Ha and less than 100 forest fires were recorded. This improvement was mainly related with the good practices introduced in forest fires prevention and management: However, these good practices didn't change anything in drought preparedness.

Perception can be estimated by the news (number, position in the journal, …) published in the newspapers. Water shortage is conditioned by several factors such as droughts, changes in the organization and distribution of water usage and changes in the societal perception of droughts. The high number of news in the regional press reflects a growing sensitivity to the lack of water, hydrological responses to changes in the basin, changes in the social interpretation of water resources uses, and the utilisation of this issue as a factor in political confrontation. Impacts and the vulnerability when facing a drought vary greatly from one region to another. This variation is probably greater than the physical-spatial variation of rain patterns due to regional differences in the ways water uses are organized and the cultural perception. Usually droughts are more readily perceived in rural areas with economies strongly dependent on agriculture (Llasat et al., 2009). The perception of the urban population, on the other hand, is mainly linked with the mass-media coverage, which in its turn usually increases when restrictive measures may be applied in urban areas.

There is a certain correlation between drought news and SPI-12 ($r=-0.538$, 99.9% confidence level, 1982-2007), based on 115 news items about droughts in the newspaper La Vanguardia between 1986 and 1989 (Llasat et al, 2009). The water private consumption in the Metropolitan Area of Barcelona was extraordinarily reduced during the period 2004-2008 thanks to the risk communication and water awareness campaigns. The analysis of SPI-12 and number of press news shows a good correlation for the period October 2004- April 2008, with 2005 as most severe year (SPI-12<-1,3 at the end of the year and near 169 news articles along the entire year) and July 2005, the worst period (SPI-12<-2, 30 drought news articles). There was an extraordinary rise of drought-related news articles in newspapers in 2008 (90 news items in the month of April 2008) because of two facts: the lack of good planning to solve the water shortage in Catalonia, and, especially in the Metropolitan Area of Barcelona, and the general elections in Catalonia that used the different proposals to the water crisis management as a tool of political confrontation (Llasat et al, 2009).

No seasonal forecast was applied in any one of the drought events analysed here. However, in the 2004-2008 drought a forecast model based in more than 60 years of contributions to the reservoirs of the system was applied. The forecast provided the warning level for different scenarios of water resources in each basin.

During the first case of study (1986-1989), it didn't exist any official procedure to cope with droughts. The water stored in the system Ter-Llobregat arrived at the critical threshold of 20% (less than 100 hm^3 in front a maximum storage of 500 hm^3), so restrictions were almost applied in the city of Barcelona, but no official drought decree was published. As Figure 3 shows this event recorded the absolute minimum water storage in the system Ter-Llobregat and served as a starting point to improve measures against drought. The first Official Drought Decree was in 1999, when the water stored in this System was near 200 hm^3. Only in the Balearic Islands (in front of Catalonia) a decree was promulgated in autumn 1989 to regulate the granting of aid for the purchase of certified seeds to alleviate the effects of the drought (Decree 93/1989 of October 19). But in Catalonia, water restrictions were only applied to agriculture and little villages.

In the 2004-2008 episode, the Decree of Drought was promulgated twice by the Government of Catalonia. The first time it was in May 2005 (93/2005 17 May) following the proposal made by the ACA (Catalan Water Agency). The decree was intended to immediately adopt measures to save and make more efficient use of stored water in order to address the rainfall deficit in all the counties, by the restriction on the supply of water in agricultural and industrial uses including hydroelectric power. The decree provided for different levels of emergency and prioritized the domestic supply of water, a priority use according to the legislation. The decree obliged the water companies and all the municipalities to present measures of water saving and to apply them, which was not completed at 100%. The drought decree was modified (Decree 187/2005, of September 6) to further index the reserves and thus guarantee water for home use until spring 2006. The decree was applicable until end of 2005, although it was repealed at the end of November thanks to precipitation and the improvement of the reservoirs. ACA applied many measures to comply with the drought decree. Among other things, they ordered the transfer of water from the Sau reservoir to Susqueda to make the most of the resources. Sanctioning different hydroelectric companies that made intensive use of water causing some sections of major rivers to dry out and a high mortality of fish. They challenged the water companies to make better use of groundwater. This last measure resulted in a sour controversy between the ACA and Aigües de Barcelona (AGBAR) for the exploitation of aquifers of the Llobregat delta.

The Ministry of the Environment (MMA) of Spain made the first touches of alarm for drought at the end of 2004. A strong controversy was generated between the different parties, as well as between Spanish and Catalan government and water users because of the different proposals to cope with drought (desalinization plants, water transport by boats, transfers between rivers, …). The Minister of the Environment ordered the hydrographic confederations and the autonomous communities to complete the special plans to face the drought and added that the extreme situation in 2005 was a "great occasion" to "reconsider the water consumption model". The minister announced that at that time they were doing investments for a value of 300 MEUR to alleviate the problem. They launched an advertising campaign to reduce water consumption and added that, if everyone followed the advice, in

Spain they could save up to 2,500 million liters per year. It was asked for declaring Lleida a catastrophic zone for damage to agriculture and livestock in 2005. The Government of Catalonia provided twice as many economic resources during the initiative so that the municipalities of Lleida could assimilate the extraordinary costs derived from the extreme drought of 2004-2008 and doubled the amount of the loans granted by the Agricultural Credit Institute to farmers and livestock farmers to face losses due to drought. However, these measures were considered insufficient by the different unions and organizations of farmers that made different demonstrations in Lleida and Barcelona. The Government planned to invest 1,535 MEUR, 60% of which would come from the European cohesion funds, to improve the exploitation of aquifers and the construction of new desalination plants and wastewater treatment plants.

In March 2007 the water stored in reservoirs in Catalonia was less than 42% and a new Decree of Drought (84/2007, 3 April 2007) was approved. It was operative until 13 January 2009. The Permanent Committee on Drought was established at the ACA, as an executive body for the follow-up of episodes of lack of resource and planning of actions, and the Drought Management Commission (CGS) which was commissioned the double task of drafting the new decree of exceptional and emergency measures for the management of the probable drought episode of this year, as well as the drafting and processing of the Drought Management Plan. The CGS created working groups with water users in order to coordinate the measures of management of the drought with the plans of emergency for the supply. New procedures and thresholds have been defined for the release of water from the dams (mainly Llobregat and Ter). Although they were partially applied during the drought event of 2008 (not in the 1989 event), the present structure was created after this drought event. Following these criteria, warning levels will be governed by indicators of volumes of the whole system or of the basins separately, in order to avoid imbalances between basins. Following the decree 84/2007 of April 3, the warning scenarios are the following:

- Pre-alert scenario: intensify the monitoring of the state of the reserves and actions of information and sensitivity, aimed at favoring water saving
- Level 1 exceptionality scenario or alert: situation in which, given the exceptional shortage of water resources, it is necessary to adopt the measures of water saving in relation to the uses and the environment provided for in this Decree in order to guarantee the supply in the medium term. When the level 1 last some months or dry conditions are very intense it pass to level 2.
- Level 2 exceptionality scenario: situation in which, given the intensification of the state of exceptional water resources shortages, it is necessary to adopt the restrictive measures in relation to the uses and the environment envisaged in this Decree in order to guarantee short-term supply.
- Emergency scenario: situation in which, given the exceptional lack of water resources, it is necessary to establish restrictions and extraordinary limitations on the uses of water in order to guarantee its supply

The alert and exceptionality level is defined in basis on the water stored in the reservoirs, so the thresholds change according to the basins and the month of the year. In the case of the Ter-Llobregat System the thresholds would be: a) level 1: 205-225 hm^3 (near 35%); b) level 2: 145 hm^3 (25%); c) emergency: 122 hm^3 (20%).

Summary

The drought episodes recorded between 2004 and 2008 (minimum SPI-12<-1.5 averaged for all Catalonia, punctual extremes<-3) in Catalonia were produced by a more extensive and intense decrease in rainfall than those recorded between 1986 and 1989 (minimum SPI-12<-0.5 averaged for all Catalonia, punctual extremes<-3). There was no significant change in the frequency and intensity of heat waves recorded in those periods (the most severe heat wave recorded in 2003 did not coincide with a drought period). On average, between 1 and 2 heat waves were recorded annually. In 1986 there were severe forest fires that burned more than 45,000 ha, but between 2004 and 2008 the maximum burned area was less than 10000 ha per year and no important forest fire were produced: the plans for prevention, prediction and extinction of forest fires developed after 1989 led to a decrease in the burned area. Some flood events as a consequence of heavy rains were produced during the two drought periods, some of them with catastrophic effects: 30 September-5 October 1987, 11-12 November 1988, 11-14 October 2005, 12-14 September 2006. However, they mainly affected the Littoral region and they scarcely contributed to mitigate the effects of droughts.

The management and policy aspects improved greatly between the first and second events. In the first there was hardly any risk assessment: early warning systems for droughts didn't exist, nor risk communication campaigns, nor water awareness campaigns. The first drought decree was not promulgated until the 1999 drought. In the second event two decrees were enacted, one in 2005 and one in 2007. The first decree already helped reduce the impacts that would have occurred during the 2007-2008 period, highlighting the risk communication and water awareness campaigns. These decrees defined the different alert levels and restrictions on water distribution according to their use and establishing priorities in the following order: urban drinking water, ecological flow, irrigation, hydropower, recreational activities and decorative uses.

The number of people exposed to drought increased considerably between the first and second events: from 6,125,339 inhabitants in Catalonia and about 9,000,000 tourists in 1989 to 7,298,313 inhabitants and about 15,026,900 tourists in 2008. At the level of hydroelectric production (total approximated to 3900 GWh/year) exposure increased a bit due to the construction of the Rialb and Llosa de Cavall reservoirs. The number of hectares of irrigated land (approximately, 300000 ha) also increased a little, although the greatest changes have occurred later. However, both the number of farmers and ranchers, who were most affected by the drought, decreased between the first and second episode.

The vulnerability decreased considerably between the first and second episode. On the one hand, the drought risk perception increased considerably, both in the administration and among the citizens. On the other, three new reservoirs were created, and a small transfer was made from the Ebro to the City of Tarragona, to ensure water supply to the main cities. Throughout the second episode two decrees were proclaimed that established legal measures to reduce consumption, it was decided to take more advantage of the groundwater from the wells, and two desalination plants were built. The press helped the awareness campaigns considerably, with about 115 news items about the drought in the first episode, and about 450 in the second. It also highlighted the important conflicts, regarding the measures to be taken, between the state and regional governments and even within the governments and administrations themselves, that made the governance of the event more difficult.

Main impacts were produced in the primary sector: crop losses, both rainfed and irrigated; death of cattle, especially goats and sheep and the need to transport water in tanks. All this raised the price of primary consumer products. There were also significant losses in hydroelectric generation and in some industries. Ecosystems were greatly affected, particularly in the first event, both by forest fires and because there was no legislation protecting the aquatic ecosystem. The second event had a very large economic impact since numerous measures were taken to avoid restrictions, including the transport of water by ships.

Last comment: As a result of these episodes, a planning for drought prevention and management was created. Among the points to consider is the improvement of irrigation efficiency in order to reduce water consumption. However, the new irrigation plan is expected to increase the irrigated area considerably, leading to a paradox (Di Baldassarre et al, 2018). An increase in irrigated land in the coming years, in a context of decreased rainfall in the Mediterranean, leads to an increase in exposure and vulnerability, that is, the risk of drought.

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ID 35

Paired drought events: 1982-1983 and 2001-2009 droughts in Melbourne (State of Victoria), Australia

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Short description of both events with a focus on impacts

The city of Melbourne experienced a severe drought in the years 2001-2009. It was also known as "Millennium Drought" and it was the worst drought on record for southeast Australia exceeding the "Short but Sharp" drought (Low et al., 2015) or the also called "Great Drought" (Gibbs, 1984) occurred in the years 1982-1983 in the same region. From 2001 to 2009, the rainfall was below its median value for the longest uninterrupted series of years in southeast Australia since at least 1900 (Bureau of Meteorology data, 2019). In the years 1982-1983 the drought was short and severe, associated to El Niño.

The Millennium Drought is believed to contract economic growth in the country by 0.75 percentage points (Penm & Glyde, 2007), in terms of gross value of agricultural production, the losses can exceed A$5 billion from 2006 to 2007. In the southern Murray-Darling Basin, which spans also the state of Victoria, the regional GDP dropped of 5.7 percent and 6000 jobs were temporarily lost (IPCC, 2014). Direct drought assistance to farmers by the Australian Government amounted to $4.4 billion by mid-2010 and an estimated $70 million was lost in the Murray River region because of reduced number of visitors in 2008. On the other hand, the loss for the 1983 season accounted for A$3 billion. During the same years, the Wimmera Southern Mallee region of Victoria experienced an 80 percent reduction in grain production and a 40 percent reduction in livestock production (Steffen, 2015).

The Millennium drought contributed to the Black Saturday bushfires, i.e. a series of major bushfire events which resulted in 173 direct fatalities and increased to 180 since several people succumbed to the injuries reported during the event (Parliament of Victoria, 2010). A 4-day severe heat wave in January 2009 across Victoria and South Australia is considered responsible of 374 excess deaths over what would be expected. However, it is difficult to count the number of exact deaths caused by heatwaves as many are due to exacerbation of chronic medical conditions as well as direct heat related illness. Moreover, the heat wave caused power failures, disruptions to train services as rails buckled and air-conditioning failed (Victorian Government, 2009). Severe bushfires occurred also in the drought occurred in 1982-1983, culminated in the Ash Wednesday in February 1983, with 75 people killed (47 in Victoria and 28 in South Australia), nearly 2,500 houses were razed, and more than 8,000 left homeless (Kanarev, 1998). The drought caused severe soil erosion issues (Gibbs, 1984; Heathcote, 1988).

The Millennium Drought impacted the lives of various rural communities, as a consequence, farmers suffered from exhaustion and depression (Sherval et al., 2014). By 2010, the Australian government paid A$4.4 billion in drought assistance to farmers (Steffen, 2015). In 2009 the water level in the reservoirs serving Melbourne reached a minimum value of 25.6% of the maximum capacity (State of Victoria, 2018). In the Murray-Darling Basin, the Millennium Drought consistently damaged aquatic and terrestrial ecosystem; it was observed a substantial decline in water bird, fish, aquatic plant populations and terrestrial species such as the river red gum (Bond et al. 2008; LeBlanc et al. 2012).

Descriptions of processes between events with a focus on risk management

After the drought occurred in 1982-1983, in 1984 the Thomson Reservoir was completed. This reservoir increased the existing storage capacity by 250%. Then, the government pursued an integrated approach to respond to drought which facilitated the adoption of technical innovation and management plans (Low et al. 2015). First, the Melbourne's water companies constituted under the Victorian Water Act of 1989. Second, in 1991, the EPA Victoria Guidelines for Wastewater Irrigation were issued to provide practical information to design and operate a wastewater irrigation scheme in agreement with environmental legislation in Victoria. Then, in 1994 the National Water Reform Framework issued by the Council of Australian Governments promoted a nationally integrated approach to water management. This reform allowed Melbourne to quickly introduce supply and demand-side measures when the subsequent dry period started. When the drought started, in 2001, the Victorian government introduced a target of 20% recycling wastewater inflow to be reached by 2010, which was gotten by 2008, two years ahead. Funds were provided to increase rainwater and stormwater harvesting; environmental flows to rivers were decreased and water conservation campaigns were launched on every media (Low et al., 2015; Melbourne Water, 2019). Besides the policies to decrease the water demand, also strategies to improve water-efficient appliances and to increase the water supply were pursued.

Event comparison in respect to drought hazard

During the drought occurred in 2001-2009, the timing and magnitude of soil moisture, streamflow, and groundwater deficits changed by up to several years. Rainfall declines in streamflow was greater than in normal dry years (Van Dijk, 2013). The evolution of the 6-months standardized precipitation evaporation index (SPEI) is shown in Figure 1. The SPEI reaches values of -2 for both drought events, assessing the severity of the two periods as extremely dry. During the drought event occurred in 1982-1983, the minimum SPEI value was equal to -2.04, with a mean value of -1.14. While for the Millennium Drought, the SPEI reached a lower value, i.e. -2.24. The mean value was equal to -0.86 (Global SPEI database, 2019).

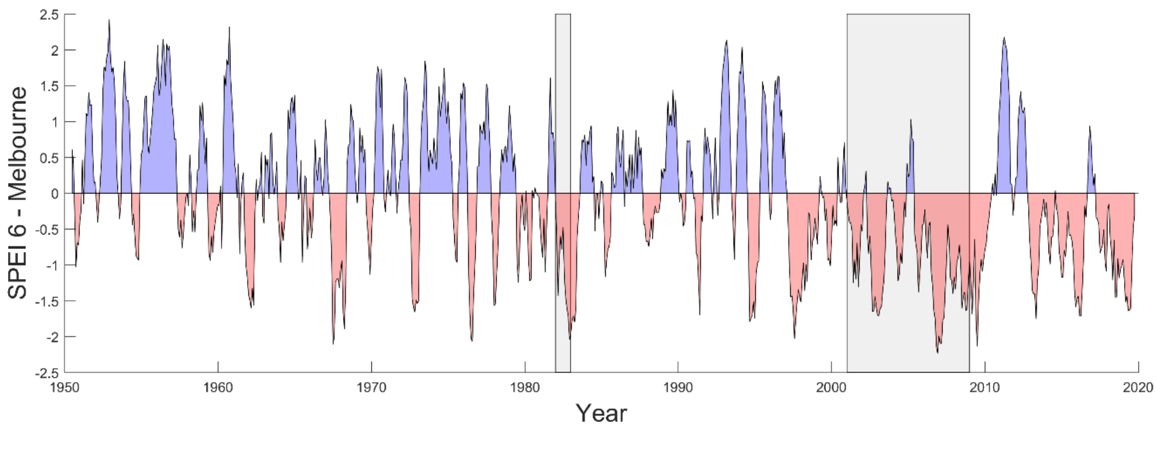

Figure 1. 6-months standardized precipitation evaporation index (SPEI) for Melbourne. The grey shaded areas correspond to the two drought events occurred in 1982-1983 and 2001-2009, respectively (Global SPEI database, 2019).

Event comparison in respect to exposure

Melbourne is the second most populous city of Australia, nowadays it counts around 4.1 million habitants. The population growth and the dry periods boosted the construction of several reservoirs that increased consistently the water storage, Figure 2. Melbourne's water supply history can be seen as an example of how reservoir expansions can partly contribute to increase water consumption (Di Baldassarre et al., 2018).

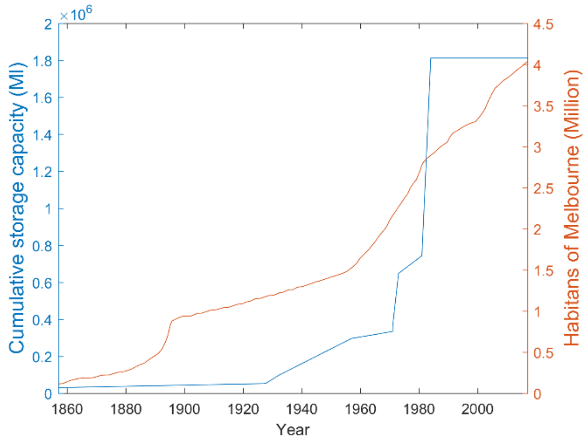

Figure 2. Population (million habitants) and water storage capacity (in megalitres) of Melbourne (ABS, 2019; Mckenzie, 2020).

Event comparison in respect to vulnerability

Victoria has developed water resource planning and infrastructures in response to its climatic variability, including severe droughts. The capability of Victoria to manage severe drought can be partly based on its water entitlement and planning frameworks. As the magnitude of the second drought event was much higher than the first one, the management strategies were also different. During the drought occurred in 1982-193, the stage one restriction was launched to decrease the use of water. In 1984, the campaign "Don't be a Wally with Water" was launched to raise the awareness of people and change their attitude toward wasting water (Melbourne Water, 2019). To extinguish the bushfires occurred in 1983, it took about 16,000 firefighters, 1,000 police officers, 500 Defense Force personnel and numerous numbers of volunteers about four days (Jones, 2007). After the drought, the State base amounts under the Natural Disaster Relief Arrangements (NDRA) agreements were increased significantly. The economic support includes, among the others, concessional loans to primary producers for carry-on, restocking, or restoration purpose

In 2002, the Stage 1 water restriction was imposed for the first time after 20 years. In 2005, the Victoria Uniform Drought Water Restrictions Guidelines introduced a four-stages water restriction protocol. From the beginning of the Millennium Drought to its end, the per capita water demand halved of its initial value by implementing policies and programs (Grant et al., 2013). In January 2007, Melbourne was posed on water Stage 3 restrictions. While in April 2007, Stage 3a was imposed. The Stage 3a was introduced to reduce the likelihood of needing to impose Stage 4 restrictions in metropolitan Melbourne. In 2008, Victorians were challenged to respect the limit of 155 litres per capita per day, i.e. the so-called T155 campaign. It was found that without these extensive campaigns to reduce water consumption, Melbourne would have run out of water by the end of 2009 (Office of Living Victoria, 2014). The campaign was successful and it ended in February 2011. At the same time several campaigns were promoted to raise the awareness about wasting water and new permanent water restrictions were implemented. Plans to augment the water supply were also pursued. In 2009, a treatment plant with a capacity of 21 GL/year was completed to use the water stored in the Tarago reservoir for drinking purposes (Cinque and Jayasuriya, 2010). In 2010 the North–South Pipeline with a capacity of 75 GL/year was completed to carry water from the Goulburn River to Melbourne's Sugarloaf Reservoir. On the same year, the Wonthaggi Desalination Plant was initiated, while started operating in 2012 producing up to 150 GL/year of water for Melbourne and the surrounding region. Water retailers improved their networks and leakages decreased by approximately 40% between 2000/2001 and 2010/2011 (City West Water, 2011).

Moreover, after the Millennium Drought, in 2013 all Australian governments agreed on a new approach to supporting drought-affected communities. The national reform aims at assisting communities and at supporting greater preparedness and capability to respond to seasonal conditions. The Victoria Government agreed on Drought Preparedness and Response Framework to make proper decisions on how supporting Victorian farmers, businesses and communities manage and recover from the impacts of drought (AgricultureVictoria, 2019).

Summary

The pair events study shows that the Millennium Drought occurred in 2001-2009 was more severe than the previous one (1982-1983). The vulnerability of Melbourne was built under the reliance on dams and reservoirs. When the largest reservoir, the Thomson, was completed in 1984, it was believed that Melbourne was "drought-proof" (Ferguson et al., 2013). Nevertheless, the increase in storage boosted an increase in water demand counterbalancing part of the reservoir benefits (Di Baldassarre et al., 2018, Garcia et al., 2020). As a consequence, the drought exposure was also higher during the Millennium Drought. The Millennium Drought forced a city counting more than 4 million habitants to find new ways of increasing water supply and decreasing water demand. The people were challenged to reduce consistently the water consumption to the limit value of 155 l/hab/day. The goal was achieved and it is found that Melbournians were actually consuming even less than that amount for 49 out of 52 weeks in the 2010/2011 financial year (City West Water, 2011). The Millennium drought raised an overall sense of cooperation and goodwill among the population (Farrelly and Brown, 2011).

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ID 36

Paired drought events: The 1987-92 and 2011-16 California Drought

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Short description of both events with a focus on impacts

In 1987-92 and 2012-17, California experienced two multi-year drought events with different levels of severity. Both of these droughts were wide-spread across California as reflected by each period receiving below-average precipitation and accumulating a below-average snowpack, while experiencing above-average temperatures (Yates, 1993; AghaKouchak et al., 2014; Griffin and Anchukaitis, 2014; Jones et al., 2015; Margulis et al., 2016; Huning and AghaKouchak, 2020; etc.). Owing to the substantial storage carryover from the preceding year, the drought impacts on irrigated agriculture were not significant during the first three years of either drought event. However, in 1991 a continuous decrease in total reservoir storages forced the state to leave more than 347,000 acres of land idled and the resulted loss of about $252 million (Dziegielewski et al., 1993). In 1992, irrigation costs increased by about $160 million in the San Joaquin Valley alone (Dziegielewski et al., 1993).

During both drought events, a portion of the reduced surface water for agriculture was compensated with additional groundwater pumping, which resulted in an additional cost of about $600 million during the 1987-92 episode for the Central Valley alone and state-wide loss of about $600 million per year between 2014-16 of which 72% were in the Central Valley (Dziegielewski et al., 1993; Lund et al., 2018). The total direct state-wide economic losses resulting from agricultural drought were approximated as $3.8 billion for 2014–16 (Lund et al., 2018). The state suffered drought-related economic losses of $2.20 billion and $2.70 billion in 2014 and 2015, respectively (Howitt et al., 2014, 2015). During these two years, the drought resulted in the loss of 17,100 and 21,000 jobs across the state (Howitt et al., 2014, 2015; Lund et al., 2018). On the other hand, the 1987-92 drought impacted planted acreage in the Westlands Water District, leading to forecasted decreases in planted acreage by 140,000 acres in 1991 and resulting in a total income loss of about $200 million (Dziegielewski et al., 1993).

During both drought events, a decrease in water availability led to a substantial cutback in hydropower productivity. During the 1987-92 drought, the hydroelectric power contribution to the total power supply decreased from over 30% to 12% (Dziegielewski et al., 1993). Similarly, throughout the deepest years of the 2011-16 drought (2014–15), the hydropower contribution decreased from 13% to about 5% of the state's electricity use (P. H. Gleick, 2016). The economic cost of substitution from other sources were estimated as $2.4 billion for the 1987-92 (Gleick & Nash, 1991) and $2 billion for the 2011-16 droughts (Lund et al., 2018). Perhaps the major impacts of the 1987-92 drought episode were related to forestry, wildlife, and aquatic ecosystems. During the most recent drought, low soil moisture was accompanied by low surface water and groundwater, and as mention above, low precipitation and snow water equivalent (SWE). Moreover, the deep soils dried during the 2012-2015 drought and Goulden and Bales (2019) linked this to significant forest die-off in California. The 1987-92 drought killed 18 billion board feet of merchantable timber (Dziegielewski et al., 1993) compared to over 102 million forest trees during the 2011-16 episode (USDA, 2016; Lund et al., 2018). Under both drought episodes, aquatic populations suffered from a reduced flow and increased temperature. The total economic loss was on the order of $10 billion over 5 years (2011-16), less than 0.09% of the state's annual economy.

Descriptions of processes between events with a focus on risk management

The first drought event was not yet apparent in 1987 because of carryover water supply in 1986. However, when its impact emerged significantly in 1988, it not only required innovative short-term solutions but also forced the state to look for long-term solutions. As a short-term solution, following the continuous decrease in total climatic water supply and depreciating stored water, the California State government urged the wholesalers of state-supplied water to reduce consumption by 10-15% and several water conservation plans went into effect (DWR, 1993). Several institutions also imposed water conservation approaches. For instance, San Francisco Water Department imposed a 25% mandatory conservation; the Metropolitan Water District of Southern California (14 million customers) requested a 10% voluntary conservation and launched a $12 million public information campaign; the San Diego Water Authority launched a public information campaign on conservation tips and water saving equipment; the Los Angeles Department of Water and Power introduced a 9.9 % water rate increase; and East Bay Municipal Utilities District set a mandatory 25% conservation and increased water rate for users with more than 1.5 m^3 per day (DWR, 1993). The major new development for a short to long term solution was the creation of the California Drought Water Bank in 1991 (Dziegielewski et al., 1993). The program is voluntary in its structure. The California Department of Water Resources acquires water in three ways: paying farmers not to irrigate or forego a portion of their supplies, obtaining surplus supplies from local water districts, and paying whole water users or whole water sellers to use groundwater instead of surface water (Loucks and Gladwell, 2008). The department then delivers and sells the acquired water to users in critical need.

In addition, an intermediate two-year drought (2007-09) inspired new water use reporting requirements, Delta planning institutions, and urban water conservation mandates. Other innovative approaches implemented during the 2011-16 drought were focused on groundwater sustainability legislation, a Delta barrier, state urban conservation mandates, more water use reporting, local responsiveness, etc. (Lund et al., 2018).

The low snowpack as well as below-average precipitation and warm temperatures, resulted in low soil moisture and groundwater and surface water levels during the 2012-2015. In fact, Howitt et al. (2014, 2015) estimated that the surface water was reduced by 6.6 million and 8.7 million acre-feet in 2014 and 2015, respectively. Groundwater pumping increased by 5 million and 6 million acre-feet in these drought years, resulting in net water shortages of 1.6 and 2.6 million acre-feet, respectively.

Large economic losses across the state were experienced during 2014 and 2015 (Howitt et al., 2014, 2015): In 2014 and 2015, losses in crop revenues of $810 million and $900 million occurred; the additional required groundwater pumping cost $454 million and $590 million; and livestock and dairy revenue losses totaled $203 million and $350 million, respectively. In 2015, approximately 540,000 acres of land were left idle because of the drought. Overall, the direct losses totaled $1.5 billion (2014) and $1.8 billion (2015), with the direct loss of jobs (e.g., farm seasonal workers) of 10,100 in 2015. The drought led to an estimated total economic loss of $2.2 billion and $2.7 billion, with total job losses reaching 17,100 and 21,000 in these two respective years.

Event comparison in respect to drought hazard

Both drought periods 1987-1992 and 2012-2015 experienced precipitation shortfalls, with the latter period experiencing greater P-ET overdrafts and temperatures that were ~1.2 degrees Celsius warmer (Williams et al., 2015; Goulden and Bales, 2019). We illustrate the paired drought events using the Oroville and Shasta reservoirs and their contributing catchments. The reservoir maximum storage on record is ~4.4BCM for Oroville and ~5.6BCM for Shasta. Three categories of droughts, including meteorological (Fig. 2), soil moisture (Fig. 3) and hydrological droughts (Fig. 4) of the paired events were compared. All droughts were identified based on a threshold method, where the 70% exceedance flow of a given day (i.e., flow duration curve was developed for each of the 365 calendar days) was used as a threshold for the hydrological droughts, and the long-term daily average was used as a threshold for both meteorological and soil moisture drought identifications.

Data analysis indicated that, the total daily climatic supply (rain and snow melt) for the Shasta and Oroville catchments were less than the long-term for 71% and 64% during the six-year drought period, respectively. Similarly, during the 2011-16 drought, in the Shasta and Oroville catchments total daily precipitation were less than the long-term average for 57% and 60% during the six-year drought period, respectively. The basin average soil moisture for Oroville catchment was less than the average soil moisture for 80% (1982-92) and 50% (2011-2016) on average during the drought periods. Shasta catchment also experienced a soil moisture below long-term average for 76 % (1987-92) and 49% (2011-17) during the drought periods. For the Oroville reservoir, over the 1987-92 drought period, prior to 1990 only minor hydrological? drought was observed from April-1988 – March-1989. The major hydrological drought started in Feb-1990 and lasted until Jan-1993. The 2011-2017 hydrological drought started in Aug-2013 and lasted until March-2016. For Shasta reservoir, similarly, prior to 1990 only a minor hydrological drought lasting between May-1987 – Nov-1987 was observed, while the major hydrological drought only started in March-1988 and lasted until Feb-1993. Like the Oroville reservoir, the major hydrological drought in the Shasta reservoir started in March-2013 lasted until March-2016. During the early periods of 1987-92 drought, the reservoir proved its worth eliminating drought with carryover storage, however, continued below average precipitation drove the reservoir to critical state in late 1990, the reservoir storage had declined to 38 % of its long-term mean storage (26% of maximum capacity). Similarly, extended precipitation deficit in the early stage of 2011-17 drought event also led the reservoir storage to decrease to about 37 % of its long-term mean storage (25% of maximum capacity) in late 2014. As such, in early 1991 and late 2014, the water agencies dependent on the reservoirs supply were facing major reductions in water supply.

Although the 1987-92 California drought predates the U.S. Drought Monitor (USDM, https://www.drought.gov/drought/states/california; Svoboda et al., 2002), we provide drought classifications for the most recent drought (i.e., water years 2012-2016, bottom panel) in Fig. 1 since it provides an indication of the drought severity, drought duration, and fraction of the state experiencing drought from 2000 onward (bottom panel). The USDM indicates that the longest duration drought (for D1-D4 classifications) that occurred in California (since 2000) began on December 27, 2011 and ended on March 5, 2019. As shown in Fig. 1, Summer/Fall 2014 encompassed the most intense period of drought in California, where over half of the state (~58%) was classified as experiencing an exceptional drought (D4). During 2014 and 2015, only January 2014 experienced a 3-week period where California did not experience any D4 classifications. From March 2014-December 2015, at least 22% of the state had D4 conditions. Throughout 2015, 32-47% of the state was classified as D4 and drought conditions (D1-D4) were seen across the entire state (~100% of its area).

The above-described statistics as well as more detailed information can be found in Fig. 1, which provides a time series of the fraction of the area of California that experienced drought characteristics. Drought classification used here and in Fig. 1 are based on the USDM (Svoboda et al., 2002).

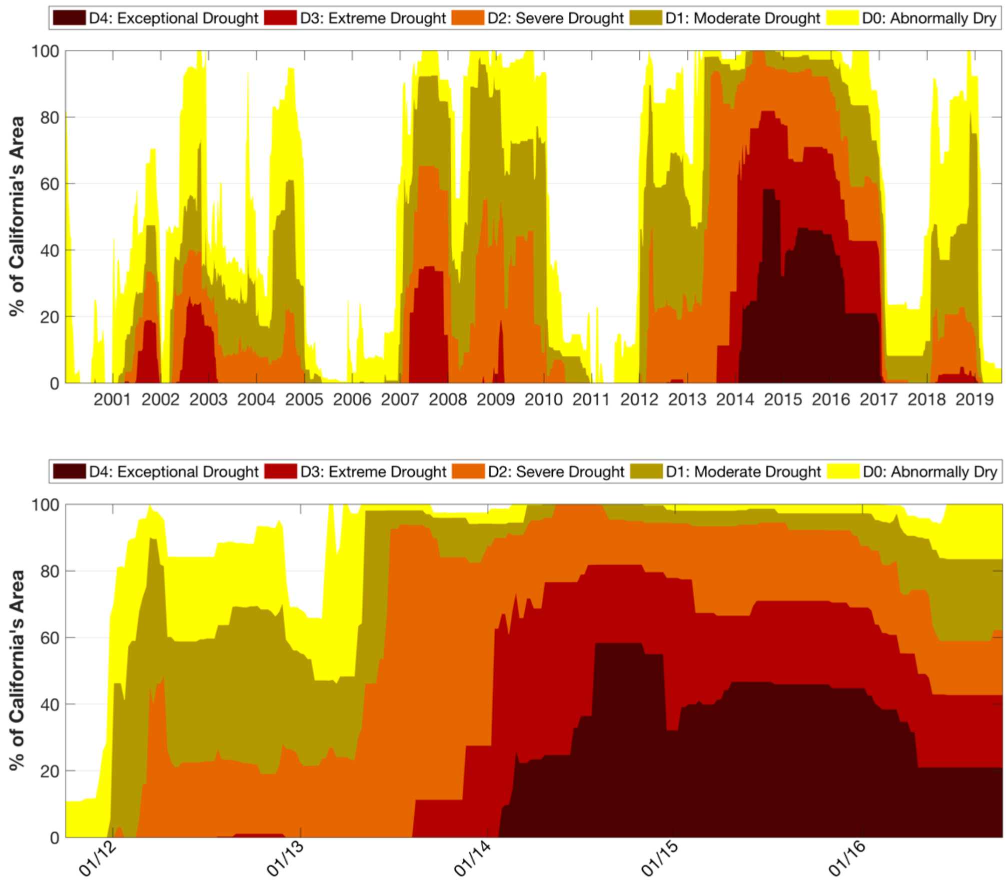

Figure 1. Periods of drought and their corresponding U.S. Drought Monitor (USDM) classifications (Svoboda et al., 2002) for California for the entire USDM record (top) and zoomed into water years 2012 through 2016, corresponding to drought years (bottom). White shading indicates the fraction of area in California that was not classified as experiencing drought. (Data source: https://www.drought.gov/drought/states/california).

Event comparison in respect to exposure

Although the severity of drought varied both spatially and temporally, the areal extent both 1987-92 and 2011-16 drought episodes was state-wide. The population of California was about 28-31 million people and 38-39 million people respectively during these two drought periods (U.S. Census Bureau: https://www.census.gov/en.html). The major impacts of the 1987-92 droughts were urban, agricultural, and instream water shortages, whereas the 2011-2016 major impacts were mainly major agricultural shortages, a decrease in water in the Delta, and a shortage of ecological and instream flows (Lund et al., 2018). In terms of agricultural production, the Central Valley of California is one of the nation's most productive regions both physically and by value of production, was the hotspot for agriculture impacts of both droughts. During the 1987-92 drought, the overall water supply reduction for irrigation agriculture amounted to 50% of the pre-drought period (1984-1986). The substitution of surface water reduction by groundwater for irrigation supplies during the 2011-16 drought led to accelerated depletion of Central Valley aquifers, exposing the area to another large-scale problem (OECD, 2017). Under both episodes of drought, cities that are hydraulically isolated were subject to the most severe impacts (Lund et al., 2018).

Event comparison in respect to vulnerability

Over the 20th century California has experienced several drought events before the 1987-92 drought, for instance, the 1928-35 drought, the 1947-50 drought and 1976-77 droughts to list a few. Such previous events have provided California's community and administrations with experience related to drought. For instance, a major impact induced by the 1976-77 drought was urban and agricultural water shortage (Lund et al., 2018) and several innovative approaches have since been devised for urban water conservation. Following this drought, the legislation at both federal and state levels were set forward. For example, at the federal level, a few laws that assist victims of drought were enacted, including the Drought Emergency Act of 1977, the community Emergency Drought Relief Act of 1977 and the Supplemental Appropriation Act of 1977 (DWR, 1978). Following those, starting from early 1983 through to 1987-89, two drought institutions like the Metropolitan Water District were sponsoring annual education programs focusing on various water issues, particularly conservation (Dziegielewski et al., 1993). Therefore, the strategies and tactical response actions during the 1976-77 droughts formed a ground framework for drought management that existed prior the 1987-92 drought.

Several lessons were learned from the 1987-92 drought, including: severe drought can change long-standing relationships and the balance of power in the competition for water; irrigation can provide complimentary environmental benefits; and market forces are an effective way for reallocating restricted water supplies (Dziegielewski et al., 1993). These lessons and additional legislation following the 1987-92 and 2007-09 droughts also guided the 2011-2016 drought response plans. As such the impacts sustained by the California state in general was minimal compared to the state economy.

Public awareness of the drought was evident during the 2011-2016 drought. According to a report released in September 2014 by the Public Policy Institute of California (PPIC), Californian voters ranked water and drought as the second most important issue facing residents after jobs and the economy (Baldassare, et al., 2014a). In the PPIC's October 2014 report (Baldassare, et al., 2014b), they again surveyed Californian voters asking them "Overall, do you think that the state and local governments are doing too much, the right amount, or not enough to respond to the current drought in California?" The survey reported the following responses: 5%: too much, 31%: the right amount, 57%: not enough, and 7% don't know. Therefore, when Proposition 1 (or the Water Quality, Supply, and Infrastructure Improvement Act of 2014) appeared on the ballot, the bond was approved by voters in November 2014. Proposition 1 was a $7.5 billion water bond that would provide funding support for water supply infrastructure projects (both surface and groundwater storage), ecosystem and watershed protection and restoration, and drinking water protection projects throughout the state (http://bondaccountability.resources.ca.gov/p1.aspx). More specifically, funding from the bond was broken into seven funding areas: 1) water storage, 2) protecting rivers, lakes, watersheds, and streams, 3) groundwater sustainability, 4) drought preparedness, 5) water recycling, 6) safe drinking water, and 7) flood management. Based on the 2017-2018 budget, more than 86% of the Proposition funds had been appropriated by the legislature (https://www.ppic.org/blog/californias-water-bond-spent/).

The 2014 and 2015 drought years were preceded by the 12-month accumulated precipitation of 2013 being less than 34% of the average (Swain et al., 2014). Therefore, an interagency Drought Task Force was already established for the state in December 2013 (https://www.ca.gov/archive/gov39/wp-content/uploads/2017/09/12.17.13_Drought_Task_Force.pdf). This group was tasked with managing water supplies, expanding water conservation, and responding to emerging drought impacts.

On January 17, 2014, Governor Brown proclaimed a State of Emergency for California due to the drought conditions, which called Californians to reduce water usage by 20% (CAState, 2014) in conjunction with an existing statewide conservation campaign—Save Our Water (http://www.saveourh2o.org/). On January 31, 2014, California's Department of Water Resources (DWR, 2014a) announced that if conditions did not change, customers should not expect to receive any additional water from the State Water Project (SWP). The SWP serves a population of 25 million people and ~750,000 acres of irrigated farmland. At this time, they reported that storage in key reservoirs was lower than it had been in 1977, which was among the driest years on record for the state, and that the statewide water content of the snowpack was 12% of average. In particular, Lake Oroville, the primary reservoir for the SWP, was at 36% capacity or 55% of its historical average for the date. The table below details the amount of water provided to various regions and contractors from the SWP and the Central Valley Project (CVP) based on the data provided in Lund et al. (2018). This same month, a Water Action Plan (http://resources.ca.gov/california_water_action_plan/) was released, detailing ways for California to improve its resilience to both drought and flood events. Additional plans and updates were issued in 2015 and 2016.

Governor Brown signed legislation in February 2014 that would provide support to drought relief in the form of $687.4 million. He further issued a proclamation in April 2014, calling for the redoubling of efforts to combat drought. During 2014, the Governor signed the Sustainable Groundwater Management Act (SGMA; DWR, 2014b), which provides a framework for pumping and recharge in both medium and high priority groundwater basins to help them reach sustainability between pumping and recharge levels to prevent overdraft. SGMA thereby established a timeline for local groundwater accounting and regulation (Lund et al., 2018).

The State Water Resources Control Board issued curtailments of the water diversions to junior water rights holders in 2014 and extended them to more senior holders in 2015, with fines issued for non-compliance. The curtailment of senior water rights holders represented the first time since 1977 that the state curtailed these rights (Lund et al., 2018). However, water rights are complicated and were fought in legal cases (Kasler and Sabalow, 2015). Enacted in 2015, Senate Bill 88 required surface water rights holders to measure and report their monthly diversions each year (Escriva-Bou et al., 2016). During this same year, the Governor required reductions of 25% for urban water use, but these cutbacks varied throughout the state from 8-40% based on local per-capita water use rates (Lund et al., 2018).

Throughout the drought, local agencies set forth and enforced their own water conservation efforts (e.g., turf rebates) and water restrictions. For instance, the Los Angeles Department of Water and Power (LADWP) and the Los Angeles County Waterworks Districts (LACWD) set up restrictions for residents irrigating lawns for a given number of days per week (LADWP, 2015; LACWD, 2014).

Summary

In California, the frequent drought episodes have created chains of lessons that have helped in real-time planning and response actions preparation for the emerging droughts. Despite the significance of meteorological and soil moisture droughts, the artificial reservoirs built across California have helped absorb the drought perturbations, at least for the first three years during both events. As such the droughts impacts on the economy were minimal compared to the state's annual economy. The inter- and intra-basin water transfers were practiced via the Drought Water Bank. The groundwater substitution for the surface water reduction came along with another price. In this case, drought buffering for the economy in part has been paid for by native ecosystems following reduced instream flows and significant depletions of aquifer for instance in the Central Valley.

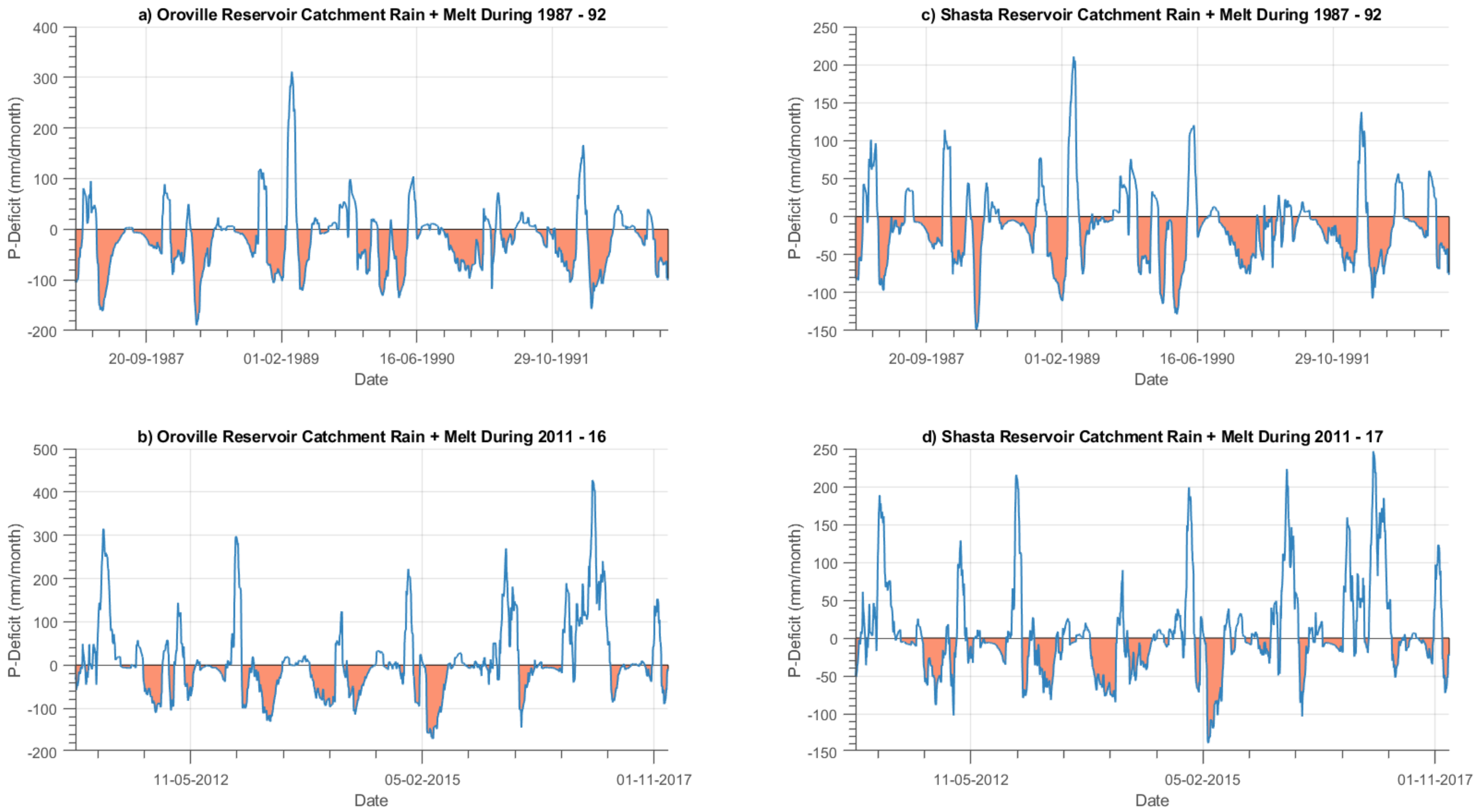

Figure 2. Climatic supply deficit during the 1987-92 and 2011-16 California droughts. The daily long-term mean of both catchments rain + melt was computed from 89 years data (1930-2018, the VIC-model meteorological forcing data). All plots are 30-day moving averages.

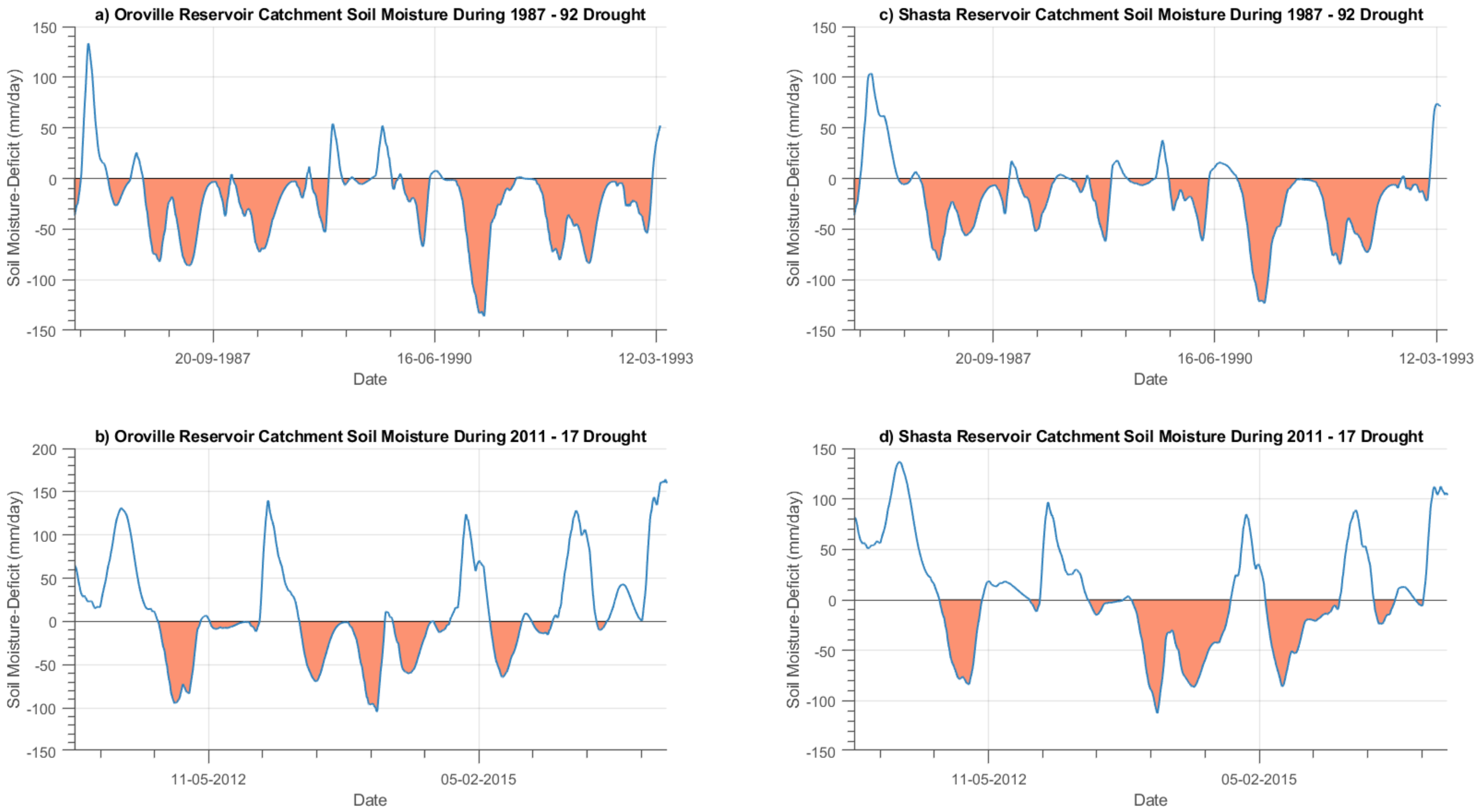

Figure 3. Soil moisture departure from long-term mean during the 1987-92 and 2011-16 California droughts. The daily soil moisture outputs from the VIC model (1931-2016, Livneh et al., 2015) were used for this analysis. All plots are 30-day moving averages.

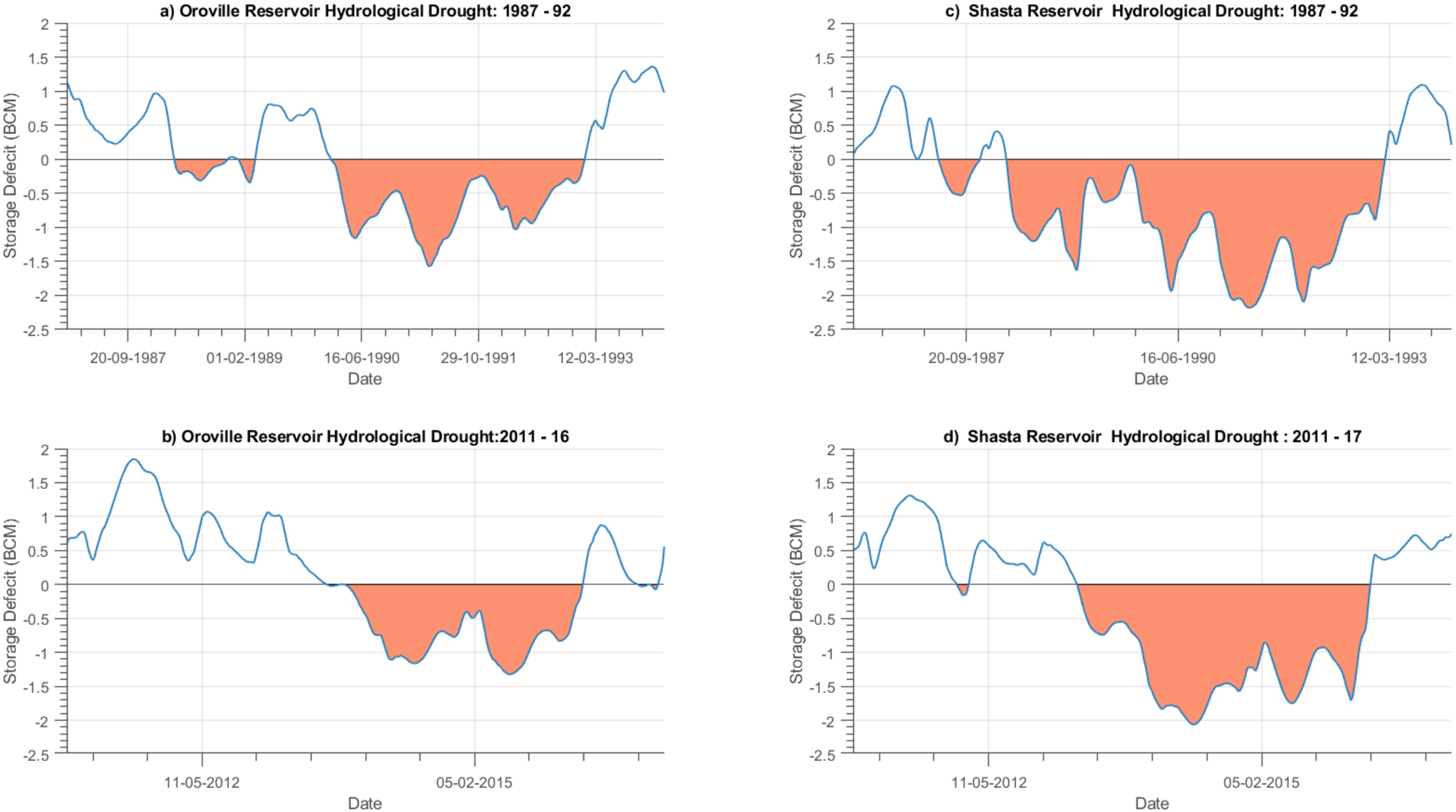

Figure 4. The Oroville and Shasta reservoirs hydrological drought during the 1987-92 and 2011-16 California drought episodes. The drought threshold used in this analysis is the 70% exceedance flow for each calendar day. Data used in this analysis are reservoir volume measurements obtained from the USGS.

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Paired drought events: 1985-1986 and 2013-2015 droughts in the São Paulo Metropolitan Region, Brazil

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Short description of both events with a focus on impacts

The São Paulo Metropolitan Region (SPMR) is the most populated area in Brazil and South America. More than 21 million inhabitants live within the 39 municipalities encompassed by the SPMR. The climate classification is Cfa/Cwa/Cwb, according to the Koppen classification (Buurman et al, 2017). A complex system of reservoirs and abstractions from rivers are responsible to supply up to 70,34 m^3/s of water to local population. This report focuses on two of those reservoirs, the Guarapiranga reservoir, whose drainage area is equal to 63,911 ha (Nobre et al., 2011) and its water production capacity was equal to 10,5 m^3/s in 1985, and the Cantareira System, which has the largest capacity of water production, 33 m^3/s before 2014, and comprises 5 reservoirs that receive water from two different river basins. The information presented in this report describes two dry events that affected the SPMR's population in similar ways. The first one occurred between 1985 and 1986, when the abstractions from the Guarapiranga Reservoir reached 60% of the normal conditions during the most severe month. The second event took place between 2013 and 2015, with abstractions from 2014 to 2015, reaching less than 40% of the regular operations from the Cantareira Reservoir System because of the very low storage level. Although some citizens voluntarily saved water, rationing and pressure reduction affected the domestic consumption in several regions.

Descriptions of processes between events with a focus on risk management

Similar measures were adopted for both events in order to reduce domestic consumption and increase water availability. Initially, the authorities promoted campaigns to stimulate voluntary water conservation and then it evolved to more sophisticated policies. While rationings were adopted in 1985-1986, new tariff policies, service area arrangements and pressure reduction were the tools used to manage the demands in 2014-2015. However, some authors argue that elections negatively affected the crisis management in 2013-2015, because some politicians avoided to mention the term "water crisis" (Buurman et al, 2017; Lucinda et al; 2019; Soriano et al, 2016). The last stage of both events' responses are the completion of physical measures, new pipelines and reservoirs were built to allocate water from other systems. Adding to this, water consumers responded differently after the drought events. Ajzenberg & Piza (1989) observed a significant increase in domestic water consumption the year after the former event, while the domestic consumption has not returned to the same level as the year before the latter event (FABHAT, 2019), indicating the event memory lasted longer after the latter event. In addition, Guzmán et al. (2017) reported economic impacts of drought events for water utilities through Severity-Duration-Frequency framework under climate change scenarios (Figure 3).

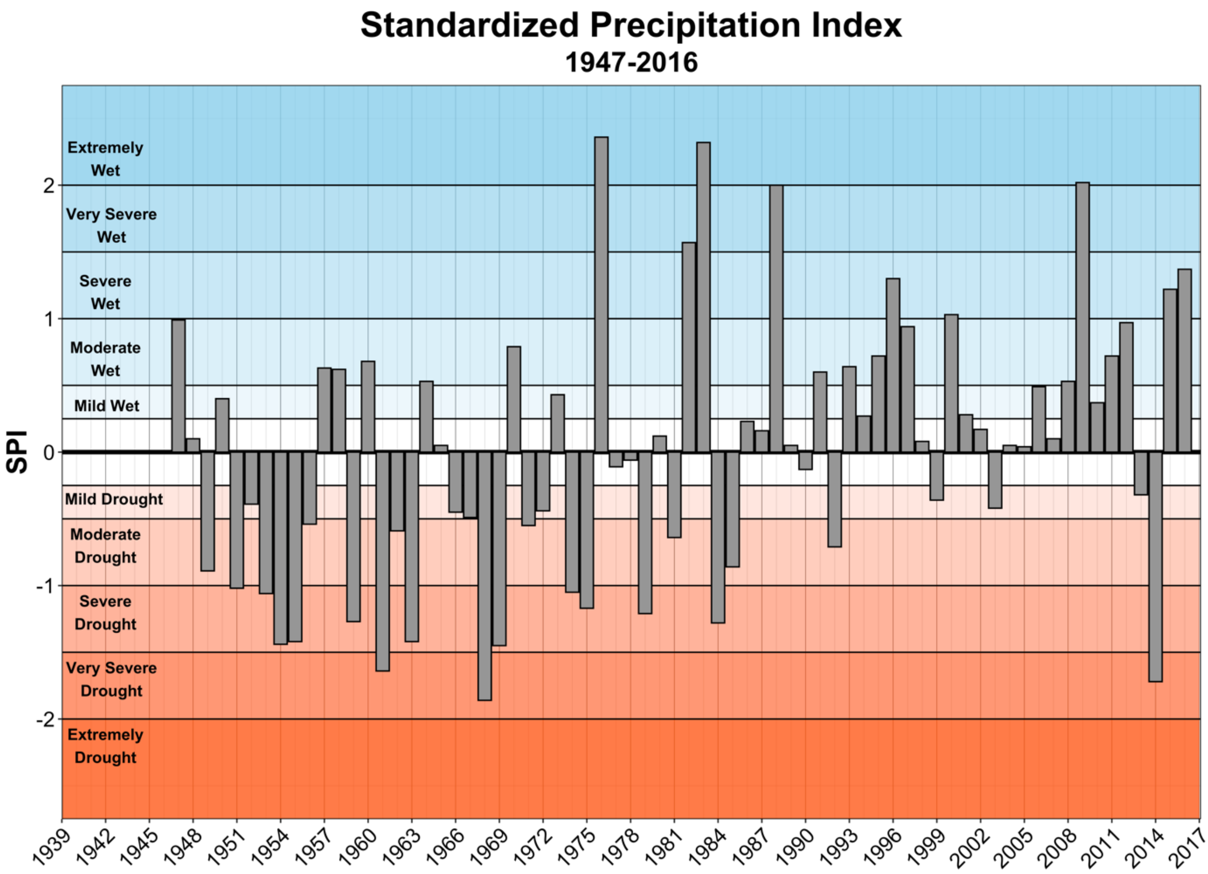

Figure 1: Classifies the rainfall according to the Standardized Precipitation Index (SPI) for each year based on historical records between 1947 and 2016.

Event comparison in respect to drought hazard

The Guarapiranga reservoir – responsible to supply water to 25% of SPMR in 1985 – reached its minimum level in January 1986, when the storage volume was equal to 7% of total capacity. The first water conservation policies were implemented in October 1985 and terminated in February 1986 Araújo (1986). Figure 1 shows that the Standardized Precipitation Index (SPI) for 1984 and 1985 was equal to -1.28 (Severe drought) and -0.86 (Moderate drought), respectively. The SPI for the two following years were classified as regular condition. Araújo (1986) highlighted that for the period between June 1985 and January 1986, the average inflow was 57% lower than the long-term average for the same period between 1910 and 1985. In addition, the records for August, October, December and January were the lowest for these months since 1910.

Similarly, the Cantareira experienced its driest year in 2013 and 2014, when the water level reached the dead storage. Nobre et al. (2016) argue that anomalies in inflow, precipitation and tempera, associated to population growth, were the key elements that resulted in this water crisis. The continuously demography growth, the highest temperatures observed since 1962, the lowest rainfall recorded since 1962, and consequently the lowest inflows for the same period, are some reasons for the worst water crisis experienced by the region. Figure 3 shows that the Standardized Precipitation Index (SPI) for 2013 and 2014 was equal to -0.35 (Mild drought) and -1.72 (Very severe drought), respectively. The SPI for the two following years were classified as severe wet. The monthly average inflow for the main reservoirs of the Cantareira System (Jaguari-Jacareí Reservoir, Cachoeira Reservoir and Atibainha Reservoir) in 2014 was 77% lower than the long-term average recorded since 1930.

Event comparison in respect to exposure

Both events affected more dramatically one out of the other dozen reservoirs that supply the SPMR. The first one affected the Guarapiranga reservoir in 1985-1986, when it served about 3 million people (25% of the São Paulo Metropolitan Area), who lived in São Bernardo, Santo André, São Caetano, Guarulhos, Mogi das Cruzes, Osasco, Carapicuiba and Santana do Paraiba municipalities. However, the effects of conservation policies affected more than 9 million as well because water from other reservoirs was allocated between service areas in SPMR. Some service areas had no water supply for 24 hours every 2 days in the São Paulo Metropolitan Region.

The second event affected the Cantareira System in 2013-2015, when it served about 8,8 million people (Marengo et al., 2015) and some industries (FIESP, 2019) in Barueri, Caieiras, Cajamar, Carapicuíba, Francisco Morato, Franco da Rocha, Guarulhos, Osasco, São Caetano do Sul, São Paulo. However, more people were affected because of changes in water tariffs in the São Paulo Metropolitan Region. In terms of population in the São Paulo Metropolitan Region, the number of inhabitants grew from 14 million, in 1985, to 20 million, in 2014. It represents 1.38% growth per year, in average.

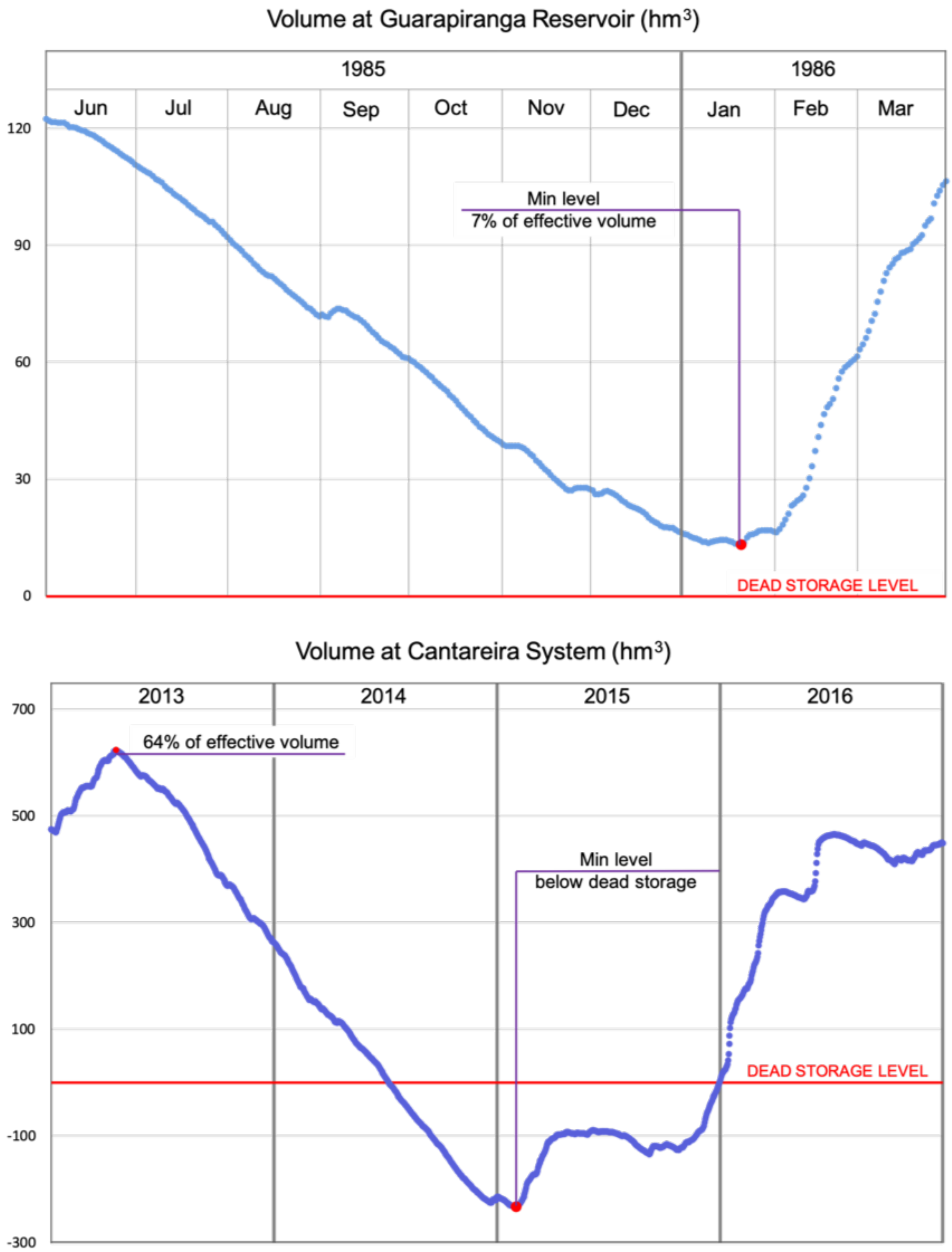

Figure 2: Volume in reservoirs responsible to supply water to São Paulo Metropolitan Region under different drought events.

Event comparison in respect to vulnerability

Araújo (1986) outlines that the water utility calculated the monthly risk of the Guarapiranga reservoir emptiness, based on time series. Once precipitation and inflow observed in the 1985 wet season were below the historical records, the first strategies to promote water savings were implemented in June 1985 (Araújo, 1986). The strategies adopted to avoid the reservoir emptiness were: Maintenance and expansion of water mains; expansion of water treatment systems; campaigns to promote water use reduction; water transfer from other systems; 62 days under some sort of water rationing (Araújo, 1986).

Since 2004, local authorities realized that water production capacity should increase to meet household and economic demands (Martinari & Peres, 2016; Richter, 2017). Even though the water utility considered the implementation of conservation policies in January 2014 (before the end of wet season), the first policies were effectively implemented in June 2014. Braga & Kelman (2016; 2020) summarized the strategies adopted as rearrangement of service areas, water allocations, communication campaigns, bonus and penalty tariffs for consumers who saved and did not save water, respectively, and pressure reduction in pipelines to reduce water losses, which led to rationing in some regions (Cambareri, 2017; Melim-McLeod, 2016; Millington, 2018; Nobre et al., 2016, SABESP, 2015). After 2018, the Brazilian Centre for Monitoring and Early Warning of Natural Disasters (CEMADEN) regularly issued hydroclimatic forecast reports based on simulations available at www.cemaden.gov.br (Zhang et al, 2018), which can better develop sustainable operation rules for water allocation (Leão & Stefano, 2019; Taffarello et al, 2018). In addition, some insurance mechanisms have been proposed as economic indicators of hydrologic drought insurance under water demand and climate change scenarios in a Brazilian context (Guzmán et al, 2017; Guzmán et al, 2020; Mohor & Mendiondo, 2017)

Finally, the water management strategies employed to promote water conservation were similar in both cases, the efforts taken in the former event were more efficient than in the later one because the supply reservoirs did not reach the dead storage volume. Two possible explanations are the intensity of inflows to the reservoir and the rationing, which was implemented in the first event and partially (only reduction in pipeline pressure) in the second one.

Summary

The water supply system in the São Paulo Metropolitan Region experienced several dry periods over time at different intensities for each water supply reservoir. In this report we highlight two major events that presented the lowest levels recorded at the Guarapiranga Reservoir and the Cantareira System (Figure 2). As a consequence of rainfall below the long-term mean for both cases, reduced inflows led to high risk of reservoir emptiness and implementation of conservation policies. Despite the fact that the former event occurred almost 30 years before the later one, the measures implemented to save water and increase water availability were similar, campaigns to promote water reduction, changes in water tariffs, water allocation and rationing or pressure reduction. Some aspects that challenged the authorities and the water utility in the later event are the constant population growth (Otto et al, 2015), anomalies of temperature and precipitation (Nobre et al., 2016), election year (Lucinda et al, 2019) and transboundary allocation to refill the Cantareira System.

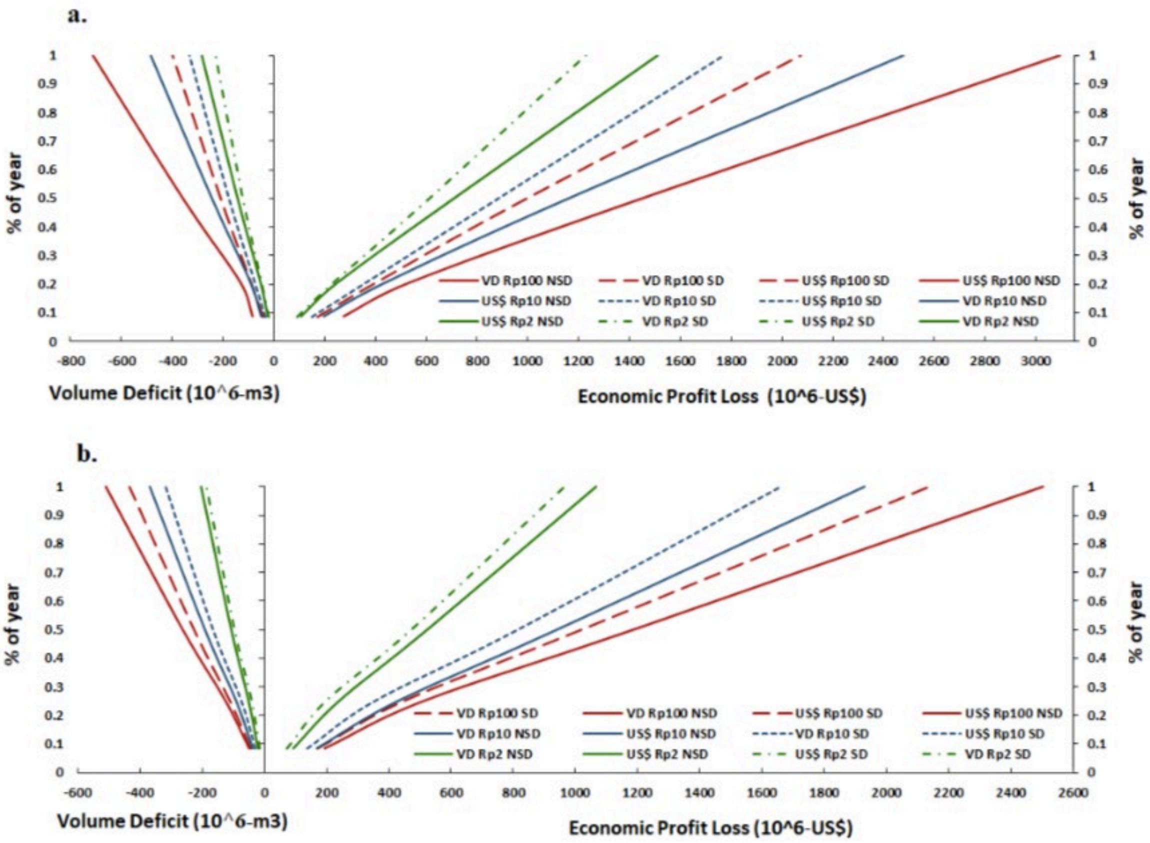

Figure 3: (from Guzmán et al. (2017)): Severity-Duration-Frequency-Profit Loss under the historical a. Eta-MIROC5 scenario or b. Eta- HadGEM scenario. Note: SD and NSD are the stationary or non-stationary demands, respectively; "VD" is the volume deficit, under return period of 2, 10 and 100 years; % of year is the drought event duration in relation to one year.

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ID 38

Paired drought events: 2003 and 2018/2019 droughts in the sandy uplands of The Netherlands

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Case introduction

The description of the two drought events (2003 and 2018) will be focused on the Raam catchment in the East of the province of Noord-Brabant in The Netherlands (see Figure 1.1).

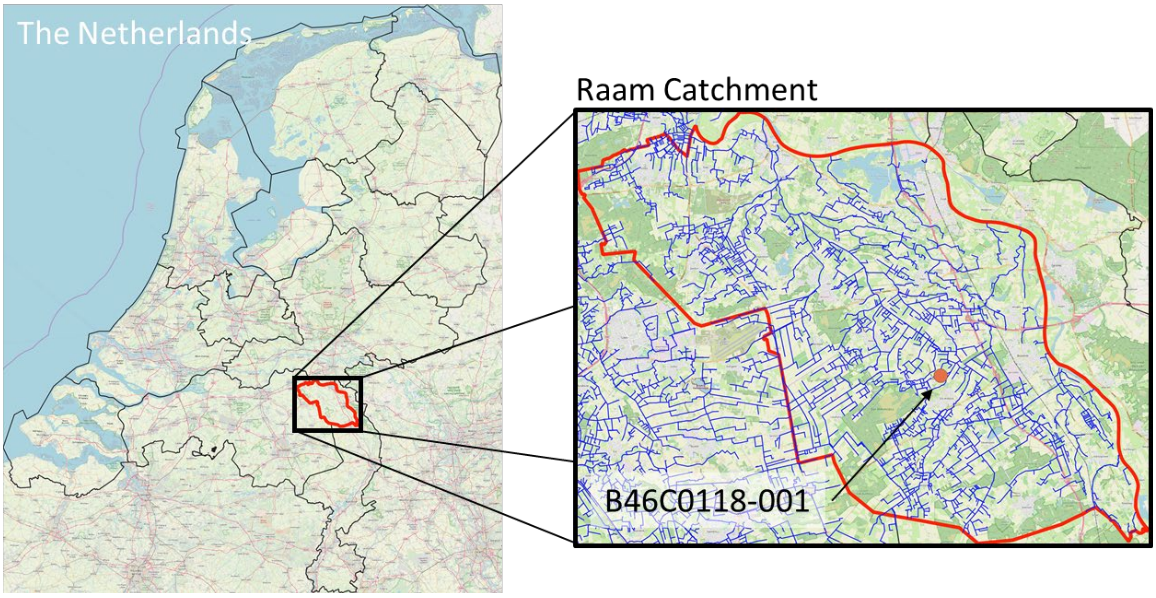

Figure 1.1: Case area: Raam catchment in The Netherlands and the location of measurement location B46C0118-001 in the Raam catchment

The catchment has an area of about 420 km^2. This catchment is known for its springs, marshes and ponds and has a variety of functions, like nature, agriculture, recreation and cultural-historic areas (Rijkers & Oomens, 2019). The area is vulnerable to drought, because a lack of precipitation may cause groundwater levels to decline which impact irrigated agriculture and nature. This effect is exacerbated by groundwater abstractions for drinking water. With a depth of at least 1.20 m below the surface level (Aa & Maas, 2018), the groundwater levels are relatively low compared to other regions in the Netherlands. Therefore, irrigation in the agricultural sector is often necessary, which takes place both from surface water and groundwater. In times of drought the waterboard can prohibit abstractions from both surface water and groundwater sources. This happened during the summer and fall of 2018 as well as in 2019. In 2003 in the Raam this prohibition was in effect mainly for surface water irrigation.

Short description of both events with a focus on impacts

The droughts of 2003 and 2018 mainly had impact on agriculture and nature. While both years can be characterized as very dry and hot, 2018 can be seen as the “extreme brother” of 2003, with a precipitation deficit of about 300 mm for the East of Noord-Brabant compared to 180 mm in 2003 (KNMI, 2018a) during the growing season (April-September). Based on the national average precipitation deficit, 2003 ended up on the 10th place of driest years and 2018 on the 5th place (Sluijter et al., 2018). The 2018 drought can even be considered a multi-year drought for this part of the country, since to date (2019) groundwater levels in the East of Netherlands have not yet recovered.

In the year 2003 Europe experienced a very dry and hot summer with temperatures over 30°C and in main parts of France and Spain around 40°C in the beginning of August, which caused many fatalities (due to the heat), and large (economic) effects in various sectors (KNMI, 2004). In central Europe, for example, the drought event of 2003 was considered the longest and most severe drought in the period 1950-2012, based on the composite indicator X-3 (from SPI-3, SPEI-3 and RDI-3) that was above 3.5 and the duration of the drought event (X-3=4.3, length=11 months) by Spinoni et al. (2016). Based on simulations with the National Water Model of the Netherlands[1], the agricultural damage of the 2003 drought in the study area is estimated at about 500,000 euro (3% of total average crop value).

The year 2018 was very dry as well. The year started with a wet, though warm, spring and ended in an extreme drought (KNMI, 2018b) with very low groundwater levels in the fall in, especially, the higher (sandy) grounds in The Netherlands (Kramer et al., 2019). Based on simulations with the National Water Model of the Netherlands, the agricultural damage of the 2018 drought in the study area is estimated at 2,200,000 euro (11% of total average crop value).

The underlaying hazard type of these droughts is the precipitation deficit, defined as the cumulative difference between precipitation and the reference evapotranspiration over the summer half year (Beersma and Buishand, 2004). This will be further explained in Section 4.

Descriptions of processes between events with a focus on risk management

In the province of Noord-Brabant the groundwater abstraction rate during the summer months of 2018 (June till September) was 27% higher for drinking water purposes than the average rate of the 10 years prior to 2018; 59 billion m^3 (Eertwegh et al., 2019). The groundwater abstraction rates for agriculture were on average 1.5 times larger in Noord-Brabant than the abstraction rate for drinking water. As a result, discharges in ditches and streams decreased, groundwater levels declined and seepage fluxes decreased (Eertwegh et al., 2019). The average abstraction rate for agricultural purposes determined over 2000-2018 is 7 million m^3/year for the Raam catchment. In 2003 the total groundwater abstraction rate was about 12 million m^3 (1.7 times the average rate) and in 2018 this almost doubled to a little over 21 million m^3 (3 times the average rate). Between 2003 and 2018 a decrease in the number of abstraction locations has taken place from slightly over 900 locations in 2003 to around 600 locations in 2018 (excluding the locations with no abstraction rate information or rates equal to 0 m^3) (source: waterboard Aa en Maas). Changes in the irrigation policy, made in the period 2009-2015, mainly caused the reduction in the number of abstraction locations. The purpose of these changes was to reduce the impact of irrigation abstractions on nature areas, e.g. Natura 2000 (Smit et al., 2014; Aa en Maas et al., 2014). The total agricultural area (horticulture, grasslands, croplands) in the Raam reduced between 2003 and 2018 with about 2,500 ha, from 26,000 ha to 23,500 ha. This is mainly the result of a reduction in croplands and, to a smaller degree, a reduction of grasslands. Nevertheless, the horticultural area more than doubled in size from about 450 ha to 1,100 ha. The high abstraction rates for 2018,

[1] https://www.helpdeskwater.nl/onderwerpen/applicaties-modellen/applicaties-per/watermanagement/watermanagement/nationaal-water-model/

compared to 2003, can be partly explained by the increase in horticultural area. Horticulture is considered a high-value type of agriculture with a higher irrigation water demand than what is needed for other types of agriculture (CBS, 2020).
To minimize the impact of a drought, several emergency response measures can be taken. The following measures were applied during the drought of 2018 by the waterboard Aa en Maas in the Raam catchment:

- Weirs were optimized to conserve as much water as possible within the catchment area while preventing flooding.
- Ditches and streams are filled with water that originates from the river Meuse. This water is transported via so called "inlets" into the streams that are connected to the river Meuse (e.g. the Sambeekse stream).
- To be sure water can reach as many springs and ditches as possible without obstructions, the sides of the streams as well as the submerged vegetation are mowed.
- When there is not enough water available, priority is given to specific streams over other streams based on their importance for the different sectors present in the area: nature, agriculture and populated areas.
- Measures are taken to prevent fish mortality in dry streams, like asking the local fishing clubs to keep an eye on the streams. They can contact the waterboard when problems occur and move fish to other streams.
- In still water, like ponds in villages and cities, temperature can increase rapidly, resulting in rapid blue-green algae growth. Warning signs are placed, and tests are carried out. Several public media are used to inform the public about the situation.
- The quality of the dikes is monitored and if needed measures are taken to strengthen the dikes to protect the area from flooding.
- Restrictions for groundwater and surface water abstractions for irrigation water purposes.

After the drought of 2018 a campaign has been started to inform the inhabitants of the area how they can contribute to preserving water in periods of drought (Aa en Maas, 2019). Unfortunately, there is no information about the emergency response measures taken during the drought of 2003 (pers.comm. waterboard Aa en Maas).

Next to the general policy changes and emergency response measures, a separate plan for creating a robust, future-proof water system for the Raam catchment was finalized in 2018 by waterboard Aa en Maas with inhabitants and other stakeholders. A first step in this plan is to set new target water levels in the surface water system. These levels are based on average meteorological circumstances, but combined with the implemented management margins, it is possible to temporarily adjust the system to be able to cope with more extreme wet or dry circumstances. Water level margins were not changed in 2003, but during the drought event of 2018 this plan was already partly implemented by raising surface water levels in the Raam catchment. This 'flexible water level management' during drought situations is now officially part of the regional policy (Aa en Maas, 2020).

Event comparison in respect to drought hazard

The standardized precipitation evaporation index (SPEI, Vicente-Serrano *et al.*, 2010) was calculated from data of a nearby automated weather station of the KNMI over the period 1993- 2019. The accumulation period was set at 3 months and a log-logistic distribution was fitted (following Vicente-Serrano et al., 2010). A drought event occurred when the SPEI value drops below -1.0 (Lloyd-Hughes & Saunders, 2002).
Several drought periods are visible in Figure 2.1; the main events are 1995-96, 2003 and 2018-2019. The meteorological drought in 2003 was less severe than the 2018 meteorological

drought. Due to an intermediate wet period in this region, the 2003 drought occurred as two drought events, whereas in 2018 the drought can be considered a continuous event. This had consequences for the impact of the drought and the propagation through the hydrological system, which were worse in 2018 than 2003. The minimum SPEI value in 2003 was -1.79 and the average SPEI value was -1.61 during the first drought event and -1.24 during the second event. During the entire year 2003, drought occurred for 132 days, where the first drought event had a duration of 51 days and the second event a duration of 68 days. At the end of the year 2003 a small third event occurred at the end of October of 13 days. In 2018 the minimum SPEI value was -2.33 and the average SPEI value during the drought event was -1.60. The drought event in 2018 lasted 171 days.

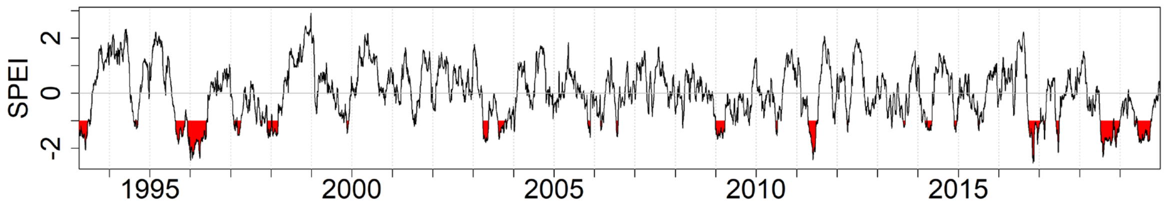

Figure 2.1 Meteorological drought events (SPEI-3) for the Raam catchment

The effect of the hazard on the groundwater system can be determined by looking at the groundwater stages throughout the year and the influence of the groundwater abstraction rates in the area. The variable threshold level method (Yevjevich, 1967; Hisdal et al., 2004) was used to determine drought from measured groundwater levels in a sub-catchment of the Raam: the Hooge Raam (Figure 2.2). The drought deficit was calculated as the cumulated difference between the threshold and the real groundwater level over all time steps in the drought period (red colored area in Figure 2.2). Groundwater levels were available from May 2003 to December 2019 on a monthly resolution. In terms of groundwater levels, the 2003 drought was clearly less severe than the 2018 drought. The 2003 groundwater drought event lasted 2 months and had a total drought deficit of 0.15m. The 2018 drought already lasted 18 months by the end of 2019 and continued in 2020. The total drought deficit until the end of 2019 is 5.96m.

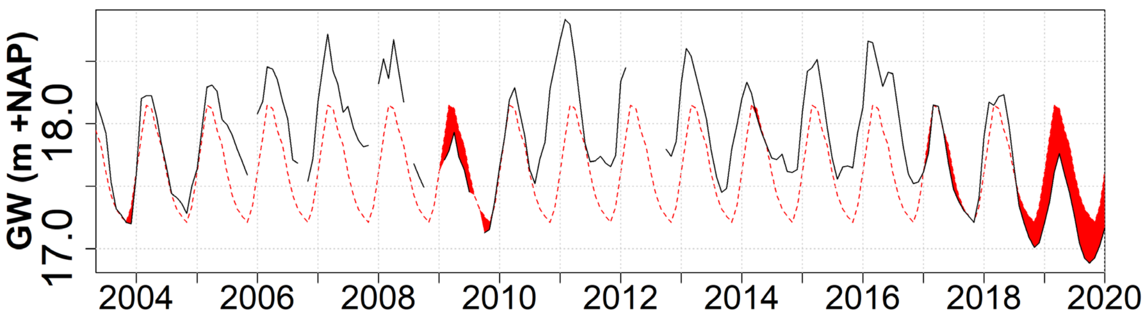

Figure 2.2: Drought events in groundwater levels for the Hooge Raam in the Raam catchment area for the period 2003-2019

To obtain insight into the potential drought impact in the area, a model analysis was performed for the Raam catchment where groundwater measurements were available for both 2003 and 2018: B46C0118-001 (see Figure 1.1 for the location). These measurements were compared to the simulated groundwater levels by the LHM model (national hydrological model of the Netherlands). This model is run at a 250x250m horizontal resolution for the year 2018 with a warm state taken from a 30-year simulation with historic data prior to 2018, with accurate drinking water abstraction rates. The model calculates the irrigation abstractions based on the locations known from the so-called "LEI-counting" of 2010. The simulated groundwater levels for the year 2003 are taken from an existing 30-year LHM-simulation, fed with long-term average groundwater abstraction rates. Figure 2.3 shows the timeseries for 2003 and 2018 for both the modelled groundwater levels and measured groundwater levels. If we look at the differences between the modelled and measured groundwater levels, the model simulates a larger decline in groundwater level over de summer half year (difference model max-min=1.4 m) compared to the measurements (difference measurement max-min=1.1 m) for the 2018 event. In contrast, the model simulates a slightly smaller groundwater decline (1.3 m) compared to the measurements (1.4 m) for the 2003 event. In 2018, emergency response measures were implemented in practice, but these are not accounted for in the model. The model simulation thus represents groundwater decline in case no emergency measures are taken during the event. Comparing modelled and measured levels of 2018, it seems that the emergency measures taken during the drought of 2018 limited the decline of the groundwater level and facilitated recovery. In 2003, in contrast to 2018, fewer emergency measures were implemented and the public awareness was probably lower, leading to a larger decline than 2018 despite the smaller drought hazard (in terms of precipitation deficit).

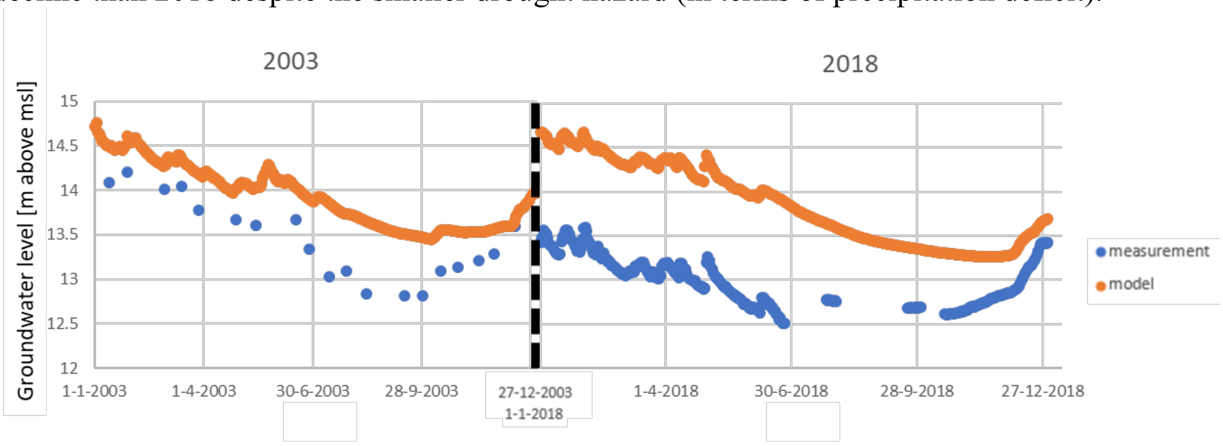

Figure 2.3: Measured (blue) and modelled (orange) groundwater levels for 2003 and 2018 for location B46C0118-001 in the Raam area. Top of borehole location is at 14.79 m a.m.s.l. and RD (new) coordinates: x=188896, y=405642. The model used to calculate the groundwater levels at this location is the LHM (national hydrological model of the Netherlands)

Event comparison in respect to exposure

For the drought in 2018, Van Hussen et al. (2019) analyzed the economic consequences of the drought for the Netherlands by data analysis of the following sectors: agriculture, shipping, water (crisis) management, drinking water, urban areas, industry, recreation, energy and nature. For the Raam catchment the sectors "agriculture" and "nature" were mainly exposed during the drought events of 2003 and 2018. Where in 2018 large parts of the Netherlands experienced the impact of the drought to some extent, in 2003 mainly the western part of the Netherlands was exposed to water shortages (Groen et al., 2004) as a result of a high precipitation deficit. This can also be seen from Figure 2.4, which shows the continuous potential precipitation surplus (the reverse of the precipitation deficit). The Raam catchment is indicated by the white box. The whole catchment was exposed to severe drought circumstances in 2018 with a precipitation deficit of more than 200 mm everywhere and more than half of the catchment experienced a deficit of more than 300 mm. In 2003, on the other hand, only half of the catchment was exposed to a precipitation deficit between 200-240 mm. The other half had a precipitation deficit of about 150 mm. So, the exposed area in 2018 was larger than in 2003.

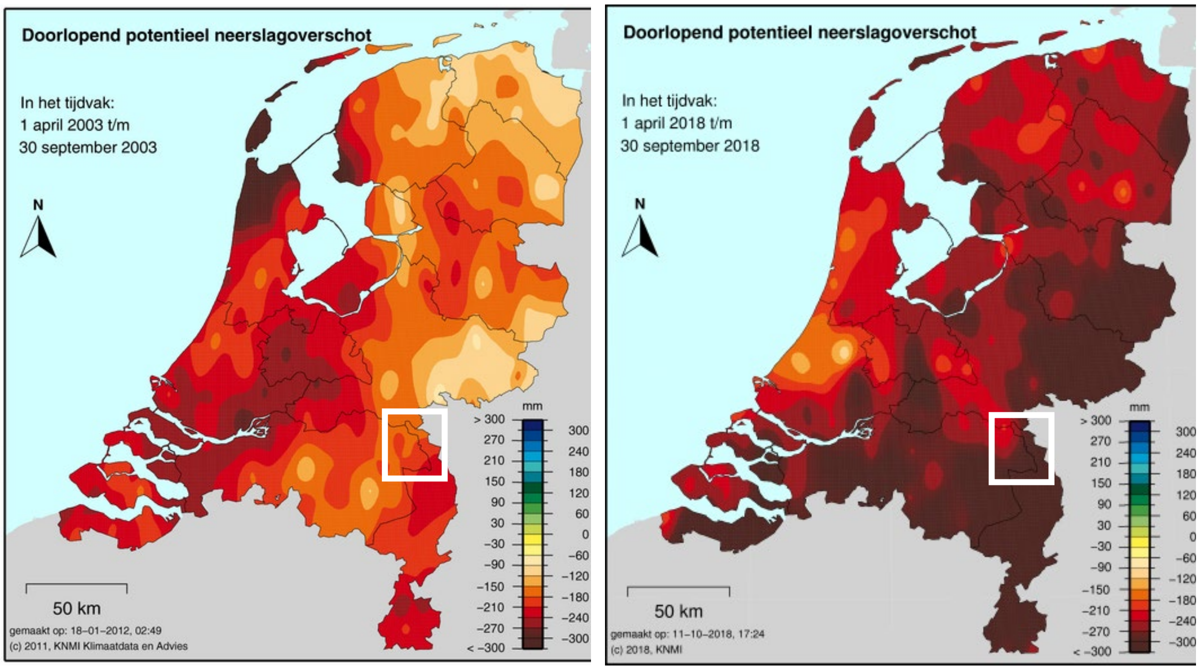

Figure 2.4 Continuous potential precipitation surplus [mm] for the years 2003 (left) and 2018 (right) over the growing season (KNMI, 2018a). The white square indicates the case study area; Raam catchment.

In terms of how the public experiences a drought event, there is a difference between being exposed and feeling that you are exposed to a drought event. The extent to which people experience to be exposed to a drought partly depends on the media attention. In 2003, for example, the media particularly focused on whether or not saltier water should be let into a certain water management area to be able to maintain the water levels, the alternative fresh water supply in the western part of the country, and peat dam breaches (Groen et al., 2004).

Event comparison in respect to vulnerability

The dry summer of 2003 created awareness by governments on different levels as can be seen in the letter written by the state secretary of traffic and water affairs to the Dutch national government (Schultz van Haegen-Maas, 2004). In both years, emergency measures were taken to reduce damage for the different sectors. Both years had at least one severe heat wave, which increased the number of heat casualties. There are no specific numbers known for the Raam catchment. Following the 2003 heat wave, a national heat plan (Dutch: Nationaal Hitteplan) was introduced in 2007 to warn Dutch citizens for the risks of extreme temperatures and provide them with a list of emergency measures (NKWK, 2020).

In 2003 only restrictions for abstractions from surface water were in effect. However, in 2018 both restrictions for groundwater (Eertwegh et al., 2019) and surface water abstractions were in effect. In the Aa and Maas area, including the Raam catchment, the surface water abstraction restriction was in 2018 in effect for a significantly longer period (from the 29th of June 2018 till the 1st of April 2019 (Aa en Maas, 2018) than in 2003 (from 19th of July till the 8th of August (Waterschap de Maaskant, 2003). Besides, as mentioned in section 3, the number of groundwater abstraction locations was reduced in the Raam area between 2003 (around 900 locations) and 2018 (around 600 locations) due to the changes in the irrigation policy (Aa en Maas et al., 2014).

Since 2017, in case of a potential water shortage or drought, the Dutch national commission for allocation of water (LCW) sets up a so-called drought monitor in which the current situation and forecasted water shortage or drought is described. The information is based upon data from the waterboards, KNMI and Rijkswaterstaat (the executive agency of the Dutch ministry of infrastructure and water affairs) and focusses on the meteorological conditions, river discharges (Rhine and Meuse), groundwater, water temperature and quality, and regional exceptions and special cases (Rijkswaterstaat, 2020). From 2015-2019, the national fire brigade has developed a national early warning system to improve prevention of bush fires in the nature areas in the Netherlands by making use of satellite data as input for a sophisticated fuel model and a bush fire spreading model to come to a more local and detailed view on the risk of bush fires in the Netherlands. This system gives a forecast for the coming 24 and 48 hours and was finalized at the end of 2019 (Nederlandse Brandweer, 2020).

Prioritization per category of water use in case of water shortage is laid down in the law of the Netherlands after the drought event in 2003. Category 1 contains dyke-stability, irreversible land-subsidence and soil-type related nature. Category 2 contains drinking water supply and energy production. Category 3 contains temporal artificial irrigation for cash crops, and industrial process water. Category 4 contains navigability, agriculture, nature (reversible damage), industry, water recreation and inland fishing. Category 1 always prevails over category 2, category 2 prevails over category 3, and category 3 prevails over category 4. Prioritization within categories 3 and 4 are subject decisions made by regional governments (LCW, 2019). This so called “verdringingsreeks” was carried out for the Netherlands in general and served as a guide for the national water distribution in 2018 and restrictions of the groundwater abstractions on the regional and national level (Eertwegh et al., 2019). Based on the changes made in the irrigation policy between 2009-2015, the waterboards of the province of Noord-Brabant (including Aa en Maas) realized that they might need a more detailed version of the “verdringingsreeks” specifically for their management area to be able to better cope with drought events. A consequence of this could be that the abstraction restrictions for irrigation purposes will not be restricted to grasslands only, but will be extended to other crops and small licensed abstractions as well (Aa en Maas et al., 2014).

Summary

This case compared the 2018 drought with the 2003 drought for an area in the Netherlands, where agriculture and nature areas were impacted by a decline of groundwater levels. Agricultural impacts were largest in the non-irrigated areas. Nature impacts were largest in the areas where groundwater abstractions continued for both agriculture and drinking water. Impacts on nature included drying out of local streams and a biodiversity loss of vegetation species (Eertwegh et al., 2019).

In terms of hazard, the 2018 drought was more severe with a precipitation deficit of 300 mm compared to 180 mm in 2003 in the Raam catchment. Consequently, groundwater drought lasted longer in 2018 and continued throughout 2019 (18 months and still counting versus 2 months in 2003, see section 4). The modelled groundwater levels (with a change in hazard and abstraction rates but equal system characteristics) show similar patterns as the measured groundwater levels, only higher absolute values. Differences between modelled groundwater levels for 2003 and 2018 are mostly the result of the differences in the hazard and the abstraction rates and are less affected by changes in system characteristics (e.g. land use type), where differences between the measured groundwater levels of 2003 and 2018 could be caused by differences in hazard type, abstraction rates as well as system characteristics. From this it can be concluded that differences between the modelled and measured groundwater levels are mostly the result of the differences in the hazard and abstraction rates, and that

changes in system characteristics are not significant between the two events, because patterns in the simulated groundwater levels were similar to the measured levels.
It seems that the 2018/19 drought has more policy implications than the 2003 drought. The province of Noord-Brabant (responsible for groundwater policy making) mentioned a large increase in awareness among all stakeholders (including the agricultural sector, nature organizations, drinking water companies, waterboards and ministries of the Dutch government), which leads to several actions aimed at system understanding (inventory of abstractions, checks whether users comply with the abstraction permits) as well as a stakeholder process to change the groundwater policy. It is expected that this will lead to a range of drought risk reduction measures in the near future, including local measures at the farm level aimed at buffering water in the soil, limiting groundwater abstraction rates, and regional measures to increase the buffer capacity of the soil. If this adaptation measures will succeed, it can be expected that a future drought event of a comparable severity will have a smaller impact.

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ID 39

Paired drought events: The 2004/05 and 2015/16 droughts in the Central Highlands region of Vietnam

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Short description of both events with a focus on impacts

The 2004/05 and 2015/16 Droughts

The Central Highlands region (Figure 1), comprised of five provinces, namely Kon Tum, Gia Lai, Dak Lak, Dak Nong and Lam Dong, has been repeatedly identified as one of the most drought prone regions of Vietnam, together with the South Central region (especially the southern Ninh Thuan and Binh Thuan provinces). It also roughly encompasses the combined river basins of the Sekong, Sesan and Srepok rivers. Every year, the Central Highlands area of Vietnam is exposed to a number of different climate related hazards such as droughts and floods, the former generally occurring during the dry season (Nov-Apr) and the latter during the rainy season (Mar- Oct). The more severe in the region however are droughts, which have also been occurring at a higher frequency in recent decades, owing to land use and climate change and to the overexploitation of water resources (CCAFS-SEA, 2016).

Dak Lak province, often the most drought-affected province in the Central Highlands, experienced losses of nearly 390 million USD from 2005 to 2016, according to the report of the Dak Lak Department of Agriculture and Rural Development. These droughts have had their largest impact on regions already affected by water scarcity, less developed infrastructure and poverty (Nguyen et al., 2017).

This applies to the Central Highlands region of Vietnam, which naturally undergoes significant fluctuations of rainfall during the course of a year due to the change from the rainy season (May-Oct) to the dry season (Nov-Apr). However, severe drought events in the region have recently increased due to various factors such as climate change, land use change and the proliferation of industrial crop plantations, resulting in a reduction of rainfall, depleted groundwater resources and overexploitation. The most damaging of these droughts in recent history where the ones during the 2005 and 2016 dry seasons, when large areas of agricultural land where damaged or destroyed and access to water for daily use was limited. Despite its longer duration (Oct ‘04 - May ’05 compared to Dec ‘15 - Feb ‘16), the 2005 drought was the less harmful of the two, with estimated damages of 73 million USD, compared to 230 million USD in 2016 [Central Highlands Steering Committee].

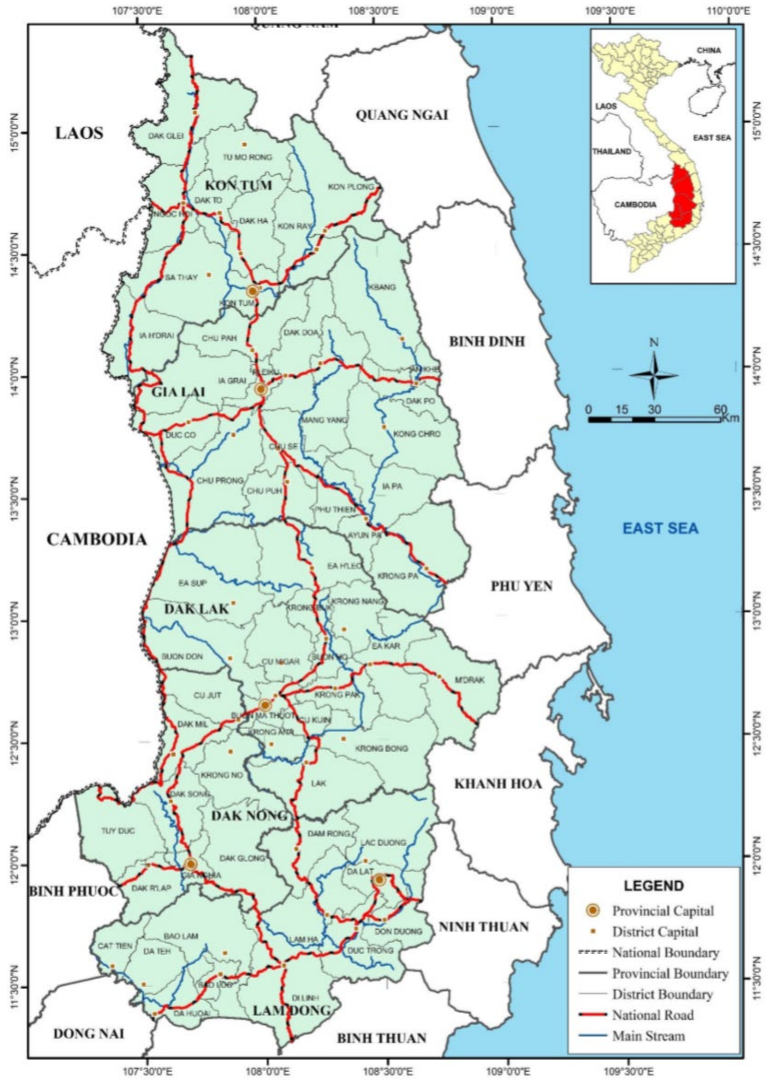

Figure 1. The Central Highlands of Vietnam (JICA, 2018)

During the time between the two droughts, efforts by the Ministry of Agriculture and Rural Development (MARD) aimed at combating drought where pursued, resulting in short- and long-term policies to encourage the planting of more water-efficient cropping systems, monitor and restrict overexploitation and increase spending on irrigation infrastructure. Nevertheless, both droughts seriously impacted the quality of life of the local population as well as the economy and further adaptation will have to be made to prevent damage in the future.

Descriptions of processes between events with a focus on risk management

Large-Scale Infrastructure

Over-irrigation has been identified by multiple reports to be a main factor that, if reduced, would make a significant contribution to water efficiency in the highlands (CCAFS-SEA, 2016; FAO, 2016). This includes waste in the large-scale infrastructure as well as underutilization of techniques like drip and deficit irrigation.

In 2013, irrigation systems relied on over 200 smaller dams of up to 10 m height, as well as over 30 large pumping stations (CCAFS-SEA, 2016). Compared to the years 2004-05, the number of irrigation works increased by approximately 30%. During the course of the 2011-2015 Infrastructure Development Plan Period, with each Province having a distinct development plan (including water infrastructure), only Dak Lak achieved their development goals, while Kon Tum almost did and the rest of the provinces fell short of theirs (JICA, 2018).

Additionally, and despite difficulties in the supply of electricity, hydroelectric plants were deprioritized in favour of preserving the necessary water discharge to ensure the daily water needs of downstream communities are met and agricultural losses are minimized, the top priorities in allocating water resources.

Early Warning Systems and Awareness Campaigns

According to the JICA study, organisations in charge of disaster prevention during the 2015-2016 drought noted a shortage of needed equipment and awareness for drought prevention and monitoring, making early warnings more difficult. This signifies room for improvement in future preparation efforts (JICA, 2018). As of 2017, shortly after the drought, noted activities of the Steering Committees for Natural Disaster Prevention and Control, specifically for drought prevention, included the maintenance and construction of irrigation infrastructure like small ponds and canals, early warnings to store water before an impending drought as well as providing water and storage tanks (JICA, 2018). During the time between the two droughts there has also been significant work done in mapping drought sensitive areas within the Central Highlands area, which can be utilized for more effective early warning systems (JICA, 2018; CCAFS-SEA, 2016).

Legal Aspects and Developments

Since September 2014, the MARD has instructed local governments to strictly implement measures to combat drought. The General Department of Irrigation, on behalf of the ministry, has been assigned to organize three anti-drought conferences in 3 regions.

These policies are aimed at balancing water resources used for cultivation. In cases of water shortage, production is to be stopped or a plan to switch to planting other crops accordingly has to be established, ensuring the production of food for livestock. Sustainable measures also include the appropriate use of groundwater and the prevention of overexploitation, except with the appraisal of specialized agencies. In addition, the implementation of drought management measures is an opportunity to restructure crops, avoid disruptive planning and limit damage caused by natural disasters.

Amongst the most important agricultural policy plans of the time have been the Green Growth Strategy (2012), the Strategy on Agricultural Restructuring towards Raising Added Value and Sustainable Development (2013) and the New Rural National Program. These have contributed to growing awareness of climate change, the proliferation of crop diversification, higher and more stable incomes and higher efficiency.

Land Use Change

The steady development in the Central Highlands region has led to severe land use changes. In particular, deforestation, urbanization and the spread of intensive plantations that require much water for irrigation have changed its landscape and created a challenge for its water resources. Deforestation especially has been drastic in the region. For example, forest area in the Srepok River Basin, one of the major rivers in the Central Highlands was at 77.2% in 2003 (Sam et al., 2019), by 2018 that number was reduced to only 39.9% (according to the Daklak Statistical Yearbook of 2018) (DSO, 2019). This means that the forest area in this part of the Central Highlands significantly decreased between the two drought events.

Agricultural Systems Changes

Agriculture and aquaculture are the main consumers of water in all of the Central Highlands provinces, taking up a combined 91% (Kon Tum) to 97% (Dak Nong) of the total water demand. Especially notable for the agriculture of the Central Highlands is the widespread cultivation of perennial cash crops such as coffee, rubber and pepper, which make up more than half of the agriculturally used land in the region. Agricultural adaptation strategies in many places have focused on directing and guiding the implementation of solutions to distribute water economically, reducing the number of irrigation times to ensure water rotation for many crop areas. During the time between the two events farmers also made progress in adopting water saving techniques such as drip irrigation, intercropping and the use of smaller water storage facilities, however some limiting factors in this progress where described as high costs, reduced yields from crop changes and a lack of knowledge of complex technologies (CCAFS-SEA, 2016). The use of shading trees to reduce temperatures and increase diversification has grown in popularity too (Nguyen and Nguyen, 2018).

Other Socioeconomic Drivers

During the ten years that passed between the droughts the Central Highlands underwent many changes in its population size and economy. A large population increase of ca. 1.65%/year from 2009-2013 was recorded by the JICA Report (JICA, 2018). This increase is in line with the target increases of the provincial governments, which is meant to support economic development.

Additionally, after the implementation of the 2011-15 Social Economic Development Plan, three of the provinces showed stable economic growth with only Dak Lak and Dak Nong not reaching their GPDP growth targets, largely due to shortcomings in the industrial and service sectors (JICA, 2018).

There was also another drought event in 2012 (Feb-Apr), which has been reported to have damaged a total area of cropland of 14,380 ha (UNW-DPC, 2014).

Event comparison in respect to drought hazard

In 2004 the Central Highlands region saw the least rainfall in 20 years. According to long-term data, the least amount of rainfall in the area until then occurred in 2004/05. The Central Highlands suffered the most serious damage from drought and the area affected by drought has been expanding over the years.

The variation in the severity of the droughts in different locations even within the Central Highlands can be demonstrated by the difference between the river basins Sesan and Srepok. The Sesan river basin in 2004/05, comprised of northern Kon Tum province as well as part of Gia Lai province showed a total water availability of 1,664 mm, only slightly less than its average of 1,781 mm, while in 2015/16 it dropped to 1,326 mm. The opposite was observed in the Srepok river basin in the centre of the Central Highlands region, where the 2015/16 water availability amounted to 1,815 mm, close to its average but was more heavily reduced in 2004/05, at 1,342 mm (JICA, 2018).

The drought at the end of 2015 was the worst the country had seen in 90 years and the cause of one of the largest agricultural losses due to droughts with losses measured at up to 230 million USD and about 86 million USD in Dak Lak province alone.

Factors that exacerbated the drought in the Srepok River Basin specifically included the Srepok 4A Hydropower Plant, which since it started operating in 2014 has been blocking the stream, essentially drying out a section of nearly 20 km running through the Ea Wer, Ea Huar and Krong Ana communes (Buon Don district), which has severely affected the local ecology, tributaries and natural landscapes, and has also negatively influenced tourism. Additionally, the El Niño event, which in mid-2014 was forecast to have a probability of 60-70%, as a result of which the risk of widespread drought was identified. Previously, the storm No. 5 had been forecast to cause heavy rainfall in the coastal areas of the South Central and Central Highlands, about 400-500 mm, but the actual rainfall was insignificant, with the Central Highlands region seeing almost no rain at all. Because of this, the rainy season in 2015 ended about 20 days earlier than expected and the rainfall reached only 60-70%. This drought was further exacerbated in 2016 with the Central Highlands provinces affected by El Niño from March to April experiencing a drought that reached dimensions only comparable to those in 1998 and 2004.

In addition, there had been no rain in the Central Highlands for four months, resulting in dry reservoirs at 30-40% of their capacity. In early March, the dry season started in the Central Highlands, so coffee and pepper trees suffered from severe water shortage, leading to heavy losses. By the end of February 2016, in the whole region about 2,865 ha of rice where forced to stop production, 1,100 ha of rice where at risk of loss of crops and over 40,000 ha of crops (mainly coffee and pepper) lacked irrigation water.

In comparison, the 2003 El Niño that influenced the drought in the following year was ranked by the Earth System Research Laboratory (part of NOAA) as the strongest such event since 1998 and has been the second strongest since, only surpassed by the 2010 El Niño. Concurrently, in 2004/05, the usually four months long dry season lasted from October to May, starting earlier and ending more than one month later than normally, with first mayor rainfalls, measured at 11.3 mm in Buon Ma Thuot rain gauge (capital of Dak Lak province), only arriving on May 7th 2005.

Event comparison in respect to exposure

In 2004/05, about 110,000 ha of annual crops were damaged, of which 73,713 ha were lost, with total estimated losses of 800 billion VND (34.5 million USD), as stated in the preliminary assessment of the Drought Survey Team in four Central Highlands provinces (Kon Tum, Gia Lai, Dak Lak, Dak Nong).

The survey team reported that 60,000 ha of corn crop and 10,000 ha of upland rice had their harvest reduced to only 15% of the expected yield, all 6,750 ha of cotton were damaged 100% and about 200,000 ha of coffee saw their production reduced by 130,000 tons. Additionally, it was reported that more than 1.1 million people lacked access to water and more than 500,000 suffered from hunger.

During the 2004-2005 dry season, damages of over 1,700 billion VND (73 million USD) where caused and over 30% of the population lost access to running water. Even more extensive, the 2016 drought affected almost all of Vietnam, 52 out of 63 provinces, and caused an estimated total damage of over 670 million USD and 230 million USD for the Central Highlands alone (60 million USD for the Daklak province (CCAFS-SEA, 2016). Of all the people suffering from the drought in the Central Highlands, two million lacked fresh drinking water, 1.5 where in need of food aid and 1.75 were reported to have lost their livelihood (CCAFS-SEA, 2016).

A different study (FAO, 2016) found, based on interviews that in Dak Lak and Gia Lai provinces roughly 60% of households could not plant crops at all during the drought, while only 15% reported not to have received losses during the drought. Of all the food crops affected, rice was the hardest hit with losses of 90% reported, while vegetables and cassava yields received relatively smaller losses of 42% and 57%, respectively. Perennial crops like coffee, rubber, pepper and cashew, which are widely used as cash crops in the Central Highlands where received widespread damage. Although they are in theory more drought resistant than annual food crops, losses of plants or even whole plantations where more costly and harder to replace, since newly planted trees will need years until they can be harvested. Results for coffee, rubber, pepper and cashew where reported as 82%, 60%, 79% and 80%, respectively.

Animals were also heavily affected with ca. 14,000 heads of cattle and thousands of smaller animals reported as sick in the Dak Lak and Gia Lai provinces alone and over 6,500 dying in the entire country (FAO, 2016).

Event comparison in respect to vulnerability

Development in Agricultural Insurance

Much has changed between the two droughts with regard to risk management and insurance. In 2011 the NAIPP (National Agricultural Insurance Pilot Program) was started, although it did not include any of the Central Highlands provinces. The results of this program are nevertheless still be relevant to future development in insurance policies for the Central Highlands region (Khoi et. al, 2017).

Before that, in 2009, the Decision No. 142/2009/QD-TTg of the Prime Minister determined rules for government support in response to disasters in form of direct compensation, with 80% of input costs to be paid to farmers and cooperatives in the Central Highlands (FAO, 2016) Multiple insurance companies have also taken interest in insuring agricultural production in the Central Highlands such as Bao Minh Joint Stock Insurance Company for coffee plantations and Bao Viet for rubber plantations (FAO, 2016). However, these programs have been plagued by multiple issues like unpredictability of losses, reluctance to commit to insurances and high premiums (Duc, 2015).

Assistance and Coping Strategies

In 2005, the Vietnamese government decided to send financial aid as well as food aid in form of 15,000 tons of rice from the national reserve to Central Highlands and South Central region provinces. The financial aid amounted to a total of 98 billion VND (6.1 million USD), of which 15 billion VND went towards Dak Lak, 12 billion VND to Gia Lai and 10 billion VND to Dak Nong province.

In 2016, studies reported a large coverage of communities with aid, mainly in form of food (especially rice), as well as cash support and credit to alleviate financial damages, since the coping strategy of many rural households (more than 70% in villages visited in the FAO report from 2016) was to sell part of their property or mortgage it for credit. Other aid came in form of seeds and other needed supplies to help farmers recover from their losses. Varying between different locations, support was received from the government (with a total of over 45 million USD in support), local community organizations, the Farmer's and Women's Unions and the Red Cross (FAO, 2016). Livelihood diversification has been considered by many people, including intercropping (e.g. coffee with avocado and durian) and animal husbandry, especially goats, who have can be fed with by-products from farms such as acacia leaves (Nguyen and Nguyen, 2019). Attempts at reaching deeper groundwater resources by extending existing wells was also widespread but often didn't lead to the intended results. Another option for farmers included migrating in search for jobs in the provinces' cities and different parts of the country, for which mobility, education and language skills are important, putting ethnic minorities at a disadvantage.

The need of digging deeper wells in search of groundwater had been ongoing even before the 2004/05 drought, with new wells dug as part of the central water supply system at a depth of 50-80 m in Dak Lak province between 2003-2005 and up to 160 m in Gia Lai province during the same time (JICA, 2018). Migration in the Central Highlands looked quite differently in the previous decades when, between 1999 and 2009, the population of the region increased significantly (ca. 3.2% per year (CPHCSC, 2010) during in-migration, largely due to the expanding agricultural sector. Although it is noticeable that the percentage of the urban population did not increase significantly during this time, from 27.2% to 27.8%, much lower than in any other part of Vietnam. This, together with a lack of accounts of migration due to drought in this period, would suggest that amongst the factors leading to lower urban migration in the region, the 2004/05 drought did not lead to a significant amount of urban migration.

Summary

Droughts are prevalent in many regions of Vietnam, and are the main cause of disaster related damage in the Central Highlands. The region has been hardest hit in recent years during the 2004/05 and 2015/16 dry seasons, each time after the occurrence of an El Niño, which regularly have intensified drought events in the past. Additionally, climate and land use changes, specifically deforestation and the growth of industrial agriculture, have negatively influenced the region's water resources.

The Ministry of Agriculture and Rural Development has led multiple policy efforts to address the problem of droughts, including the encouragement of crop diversification, sustainable water resource management and early warning systems. Because of the greater severity of the 2015/16 drought, the issue of droughts in the Central Highlands has also received more attention in the research community, which will help contribute to mitigation strategies in the future.

Despite these efforts, the drought in 2015/16 had less severity but had larger affected area compared to the drought in 2004/05 (Ha et al., 2016), with damages of 230 million USD, almost four times as high as during the 2004/05 drought, making further development in water efficiency and drought adaption in the region an imperative for policymakers as well as local stakeholders.

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ID 40

Paired pluvial flood events: 2000 and 2015 pluvial floods in the Corigliano-Rossano city, Calabria Region (Southern Italy)

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Short description of both events with a focus on impacts

The Corigliano-Rossano is the largest municipality in the Calabria Region (Southern Italy) with a surface of 346.56 km^2, and the third one for number of residents (77,119) with a population density of 222.53 inhabitants/km^2. The territory, located on the east coast, expands from the sea level to 1185 m a.s.l. It is characterized by 18 drainage basins which flow into the Ionian Sea, and range from 3 to 290 km^2 in extension. Settlements are concentrated in two main sectors: the hilly sector (average altitude of 200 m a.s.l), where the two oldest villages characterized by a constant number of inhabitants in all seasons are located, and the coastal plain, which is an important destination for summer holidays due to its 30 km long coastline. At the coast, there are a dozen small residential areas, where the population rises sharply in July and August because the large sandy beaches attract many holidaymakers.

In the years 2000 and 2015, intense rainfall events triggered shallow landslides in the hilly sector and floods along the coastal area. In both cases, overflow of the rivers and levee failures, in combination with storm surge and backwater effects, caused the inundation of residential areas. During the 15 years between the two events, levees were built or reinforced along some stretches of the watercourses passing through the urbanized areas. For this reason, the flooded area in 2015 (about 7 km^2) was smaller than in 2000 (about 10 km^2). Both events caused direct damage to buildings, roads and railway networks, agriculture and industry, as well as indirect consequences due to the interruption of commercial and tourist activities. In both cases, roads and railroads were temporarily interrupted, and many buildings were flooded by water, mud and debris. Total economic consequences were higher in 2015. Flooding in 2015 resulted in more severe damage to buildings and roads since higher rainfall amounts in shorter time caused higher flood discharges and water levels within the urban areas. According to municipalities' reports, damage to urbanized areas and agriculture exceed 100 million euros in 2015 (Rago et al. 2021), while direct damage due to the 2000 event remains unquantified. In 2015, particularly high indirect losses occurred because tourism activities were stopped early at the peak of the holiday season in August, resulting in unquantifiable profit losses. The 2000 event took place instead in September, a month when tourist presence is significantly lower, so comparatively lower indirect losses occurred in 2000. In both events, several people had to be rescued either by volunteers or by the police, but fortunately there were no fatalities or injuries in either event.

Descriptions of processes between events with a focus on risk management

The central government provided relevant economic resources after both events, in order to support recovery from public and private damage (in 2000: € 6,214,009.40 - OPCM 3081/2000; in 2015: € 3,920,000.00 - OCDPC 285/2015). He amounts of the funding were rather not related to the amount of damage, but rather due to the following reasons. Firstly, the 2000 storm affected the entire region, and in the village of Soverato (SE Calabria) the flood killed 13 people, attracting national attention. Therefore, the 2000 event represented a break point after which high economic resources were dedicated to geo-hydrological risk reduction in the whole country, as well as in the Corigliano-Rossano city. Besides the emotional boost due to the widespread impact of the event and the intention of reducing flood risk, the central government provided more funding than in 2015, also because of a greater availability of public funds. The global financial crises (2007-2009) limited in fact the amount of available funds still after the 2015 event.

After the 2000 event, both short-term restoration interventions and long-term flood risk reduction measures were undertaken in the whole area. The national early warning system was improved. In 2000, in fact, no alerts were issued to local municipalities. The only communication sent from the National Civil Protection to local administrations consisted in a series of meteorological warnings which were ineffective in alerting the population, because these were not followed by prevention activities. After this event, both daily meteorological forecast and real-time monitoring of hydro-meteorological parameters have been entrusted to regional administrations so that, currently, different types of alerts are issued to majors of the municipalities if floods are expected. For this reason, both before and during the 2015 event, the municipality of Corigliano-Rossano received several alerts of different levels. Also, thanks to these alerts, many people were warned of possible flooding and moved to safer places during the rainstorm, so that nobody was injured or died. Still, two citizens were overwhelmed by strong currents and were rescued by the police.

After the 2000 event, moreover, flood risk maps were produced to manage the risk in the areas surrounding the water courses, limiting their urbanization and regulating the land use. After 2000, levees were built or reinforced along some stretches of the watercourses passing through the urbanized areas (Regione Calabria 2015). The structural interventions allowed containing the impact of the 2015 flooding in a smaller territory, despite still occurring breakage of several levees. A common criticism was the scarce maintenance of the stream channels, as well as of levees, culverts and bridges. Such situation amplified the effects of flooding in the urban areas close to the streams. In neither case, an efficient emergency plan was available to manage the flooding events.

Event comparison in respect to pluvial flood hazard

Both events were triggered after dry summer periods by intense precipitations associated to low pressure vortexes, which originated over the central Mediterranean because of cold/dry and warm/moist air masses convergence. The mixing of these two air masses, characterized by different temperature and humidity, originated severe rainstorms that were amplified by the orographic effect, and persisting in the same areas for three days in 2000 and almost a day in 2015.

Specifically, the flood of 9 September 2000 was triggered by an intense precipitation reaching a maximum daily amount of 192 mm, and showing a return period of 10/20 years (Petrucci et al., 2017). During the second event, occurred on 12 August 2015, the rain gauge located within the most damaged area recorded a total event precipitation of 230 mm in 17 hours. This is an exceptional value, given that it corresponds to about ¼ of the total annual rainfall, with a return period higher than 100 years (CFD, 2015, Rago et al. 2021). Rainfall data highlighted that the rainstorm was centered on the Corigliano-Rossano municipality.

Event comparison in respect to exposure

Inhabitants of the Corigliano-Rossano city increased from 73,518 in 2000, to 77,368 in 2015. In the 2000 event, 7,655 buildings were located within the affected areas, while in the 2015 event 9,508 buildings were located within the affected areas. These numbers were determined by comparing both multi-temporal aerial photographs and data provided by the Italian National Institute of Statistics. This increase in exposed buildings was associated to a growth of residents, while in other cases the new buildings were houses for vacationers. Many among those realized along the coastline suffered heavy damage during the 2015 event.

Inhabitants affected by floods, were about 49,000 in 2000 and 33,000 in 2015, however, in both cases one needs to add the thousands of vacationers coming from other parts of Calabria and Italy. There are no official data to quantify them in detail, even if the number of vacationers in 2015 peak season can be assessed as twice with respect to September 2000. Therefore, in total significantly more people were exposed in 2015 in comparison with 2000. Extension of the affected urban areas resulted of about 10 km^2 in 2000 (8 localities), and 7 km^2 in 2015 (5 localities). On the other side, flooding processes were recognized in a higher number of drainage basins in 2015 (11) than in 2000 (5), as shown in Figure 1.

Both the events affected the local economy that is mainly based on tourism and agriculture (essentially citrus groves from which fruits are exported all over the country and abroad because of their fine quality). In fact, flooding caused heavy damage to cultivated fields and put an early end to the touristic season. Especially in 2015, tourism activities were stopped early at the peak of the holiday season in August. The 2000 event took place instead in September, a month when tourist presence is significantly lower and the season slowly coming to an end anyway. Residential buildings, industries, roads, bridges, aqueducts, sewage systems and electric lines were also damaged by mud and debris transported by turbulent flows (Figure 2). During the 2000 event, the railway, the police station and some schools were seriously damaged. During the 2015 event, the railway was affected again, together with the principal roads connecting the inland settlements with the coastal zone.

Event comparison in respect to vulnerability

Some historical floods had occurred in Corigliano-Rossano city throughout the last century. Therefore, adult people living in the city had some knowledge of floods and were therefore less vulnerable than e.g. tourists who experienced their first flood in 2000. In 2015, residents had better knowledge about floods, but tourists were unaware. Sharing of information (incl. photos and videos) via social networks increasing the capacity of people to undertake emergency measures and reach safe locations. Also (as described above), early warning had significantly improved and authorities as well as citizens were better prepared in 2015.

Summary

The Corigliano-Rossano city was affected by two flooding events in the years 2000 and 2015. In 2000, flows inundated a larger urbanized area consisting of more localities with respect to the following event. Specifically, flooding processes were recognized in 5 drainage basins and 8 localities in 2000, 11 basins and 5 localities in 2015. Flooding in 2015 resulted more severe in terms of impact on buildings and roads because triggered by higher rainfall amounts concentrated in minor time, resulting in higher flood discharges and water levels within the urban areas. In both cases, flows inundated roads, buildings, industries and cultivated fields, dragging also some people towards the sea. Despite this, no fatalities resulted after the two events.

An important improvement concerned the alert system for geo-hydrological risk carried out after the 2000 event. Currently, in fact, specific alerts are issued from the regional civil protection to single municipalities, specifying the expected risk scenarios and possible timing of processes. A further improvement consisted in the realization of flood risk maps which helped local authorities to identify urban settlements exposed to flooding and to undertake measures to reduce their vulnerability.

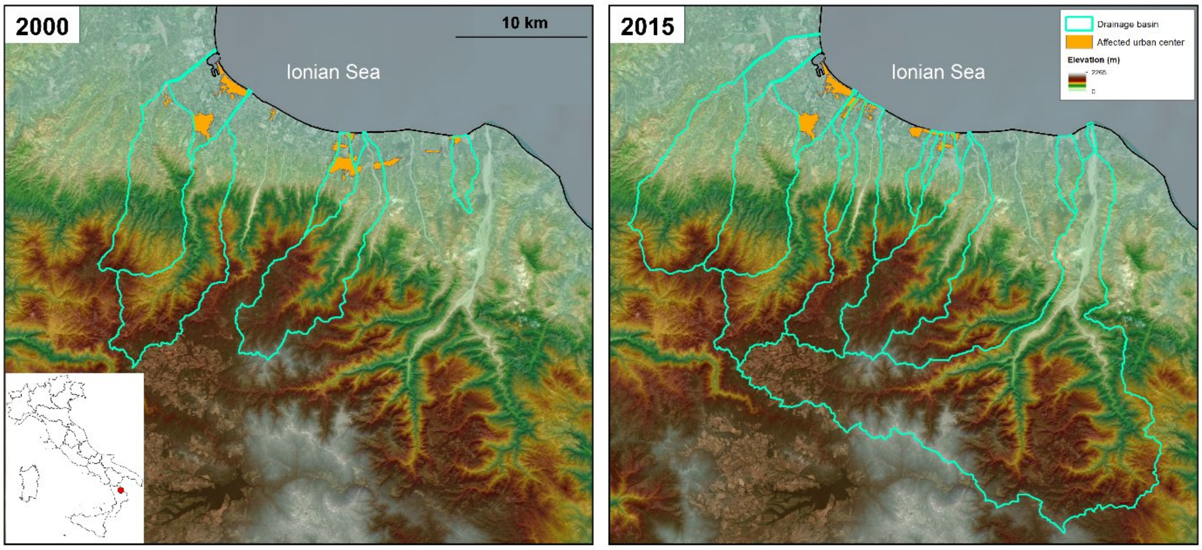

Figure 1. Overview of the drainage basins and urban centers affected by flooding processes in the considered events.

Figure 2. Photographs showing inundation of the urbanized areas located along the coastal sector. The storm surge effect is visible in the largest photograph taken on the coastline (A: http://www.strettoweb.com/, B: http://www.meteoweb.eu/, C: https://www.meteogiornale.it/, D: http://www.meteoweb.eu/).

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Paired riverine flood events: Comparison of 2017 and 2019 riverine floods in the Ottawa River Basin in Canada.

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Short description of both events with a focus on impacts

The Ottawa River Basin experienced major record-breaking flooding events in the spring of 2017 (5 April – 8 May) and 2019 (19 April – 16 May) that both impacted significant areas around the Ottawa River in Ontario, Quebec, and New Brunswick. Both flooding events occurred due to a combination of separate extreme weather events in April resulting in increased freshet and soil saturation. Record levels of precipitation received across the Ottawa River Basin between April and May of 2017 resulted in the flooding of various regions between 5th April and 8th May (ORRPB, 2018). The 2017 flood event caused more than CAD $223 million in insured damages (equal to CAD $230.06 million in 2019 value), flooded an estimated 6,171 houses in Ontario and Quebec (IBC, 2017; Teufel et al., 2019), and resulted in two fatalities in Quebec (IBC, 2017; Peritz, Perreaux, & Stone, 2017). Similarly, in 2019, above-average precipitation within the basin led to widespread flooding in Ontario, Quebec, and some regions of New Brunswick between 19th April and 16th May, causing CAD $208 million (in 2019 value) in insured damages (IBC, 2019a). The 2019 flood is estimated to have flooded 5,996 houses in Quebec and Ontario (Statistics Canada, 2019), and also resulted in one fatality in Quebec (CBC, 2019a). Since not all homes in Canada are insured for flooding, total damages caused by each flooding event are likely to be significantly higher than the values reported for insured damages.

The long-term impacts of these floods are still unknown since both events occurred recently, but psychologists and sociologists have indicated concerns over intangible impacts of recurring flood events, including flooding fatigue (Payne, 2019; CBC, 2019b). Additionally, the authorities in flood zones have since given warning to residents about secondary threats, including mold, contamination and dangerous debris left over after the floods (Silcoff, 2019). These impacts are likely going to be more severe for rural populations, Indigenous communities, and cottage house owners who were not provided provincial assistance in various cases (Silcoff, 2019).

Descriptions of processes between events with a focus on risk management

Flood risk management responsibilities for the Ottawa river are shared between three main levels of government that include municipal, provincial and federal governments, as well as local sub-watershed supporting organizations that work in partnership with municipal governments (ECCC, 2019). The two provinces, Ontario and Quebec, work in partnership with 200 municipalities within the Ottawa River Basin to manage the watershed. Supporting organizations facilitate sub-watershed level collaboration and include five Conservation Authorities (CAs) in Ontario and six Organismes de basin versant (OBVs) in Quebec [Appendix B]. The provincial governments also work closely with agencies such as the Ottawa River Regulation Planning Board (ORRPB), Ontario Power Generation, Hydro-Quebec and the International Joint Commission (IJC) for integrated management, regulation and operations of 13 principal reservoirs in the basin (McNeil, 2019). Since flooding has become one of Canada's most common and costly natural hazard (Thistlethwaite et al., 2017; Public Safety Canada, 2019; IBC, 2019b), changing weather patterns and increased concerns of flooding have prompted several conservation authorities and municipal governments in the basin to prioritize strategies that mitigate flooding impacts in their management plans even before the 2017 floods (MVCA, 2015; RVCA, n.d.; Tousignant, 2013). But technical guides and policies have not yet identified specific ways of incorporating climate change impacts into regulations, planning and permitting decisions (McNeil, 2019).

Another major problem of Canada's flood mitigation is that Canada does not have up-to-date flood maps that depict high-risk areas (Thistlethwaite et al., 2017; Forrest, 2017). And the maps that are available for public access do not effectively communicate risk to the general public (Henstra et al., 2019; Minano, Henstra & Thistlethwaite, 2019), thus compromising awareness and precaution. For Ontario, guidelines for hydrologic modelling, floodproofing standards and floodplain mapping are described in technical guides based on scientific approaches from the 1980s that are now considered outdated (McNeil, 2019). Ontario's Ministry of Natural Resources and Forestry did commission a review of floodplain mapping standards in 2016 (McNeil, 2019), but the final report, although considered to be in final draft phases, has not been published as of February 2020 (Ibid). Government of Quebec has been relatively quicker in response to the 2017 flood, announcing CAD $24 million to its municipalities to create or update their emergency action plans, as well as CAD $20 million to update flood zone maps (CTV Montreal, 2018). Quebec has released these updated new flood zone maps in June 2019 with several updates made after public consultations (Anhoury, 2019).

The federal government released a series of documents in 2016 setting guidelines to help advance flood mapping projects across Canada especially in regions where robust guidelines do not exist (Public Safety Canada, 2019; NRCan & Public Safety Canada, 2018). These guidelines are reported to have caused confusion in Ontario where the province's existing mapping guides take precedence (McNeil, 2019). The federal government is potentially planning on uploading nearly 2000 publicly accessible and user-friendly flood-maps using recent geospatial data to identify at-risk properties (MacDonald, 2019). But these federal maps have not been released as of February 2020, and the timeline of implementation is unknown.

After the 2017 floods, the federal Liberal government also earmarked CAD $2 billion to be spent over 11 years on risk mitigation and disaster prevention efforts of communities facing risks from flooding, fires and extreme weather in Quebec, Ontario and New Brunswick (Press, 2017). This 'disaster mitigation and adaptation fund' will go towards subsidies to provincial and municipal projects that are aimed at disaster-proofing communities (Elliot, 2017; Press, 2017). Most of this fund was originally expected to be spent after 2021 once projects passed the review and approval phases; however, a provision in this program allows a provincial minister to approve projects in emergency situations. Therefore, when the 2019 flooding impacted many of the same communities that were flooded in 2017 as well, the Minister of Infrastructure, announced that the approval process would be fast-tracked for flood protection projects with start dates between 2019 and 2020 (Press, 2019a). According to a media report, the federal government committed to spending $832.9 million for 90 projects as of April 2019 (Press, 2019a), but none of these projects were completed before the 2019 floods.

In terms of recovery from flood impacts, private overland flood insurance has been available to Canadians only in the last few years with only the 16 biggest insurance companies offering that option for property owners (in fact, before the Alberta 2013 floods, Canada was the only G8 nation that did not offer private insurance to property owners) (IBC, 2019b; Thistlethwaite et al., 2017). As a result, only 10-15% of homeowners in Canada are signed up for overland flood insurance according to the Insurance Bureau of Canada (IBC) estimates (Posadzki, 2017). Therefore, financial responsibility for disasters in the Ottawa River basin is primarily borne by the provincial and municipal governments and by property owners directly. High-risk flood areas, especially, have very limited insurability in Canada, and when insurance options are available for property owners, they have low caps or are very expensive (McNeil, 2019). So, most properties in high flood risk areas are uninsured (McNeil, 2019). In a 2018 report, it was noted that for every dollar of insured losses borne by insurers in Canada, three to four dollars are borne by governments and home or business owners (IBC, 2019b).

For Ontario, a natural disaster activates two recovery programs that were launched in 2016: Disaster Recovery Assistance for Ontarians (DRAO) at the provincial level and Municipal Disaster Recovery Assistance (MDRA) for municipalities, to restore essentials of properties to basic pre-flood conditions (McNeil, 2019). In Quebec, financial assistance for recovery and emergency shelter is provided by the Financial Assistance to Disaster Victims (FADV) program (Securite Publique Quebec, n.d.). The federal government also cost shares with provincial governments through Disaster Financial Assistance Arrangements (DFAA) if disaster costs exceed a given threshold, i.e. costs become high enough that provincial governments cannot cover them (McNeil, 2019). These assistance programs are not meant to be alternatives to flood insurance and cover only the essential repairs. Hence, if overland flooding insurance is available within a reasonable price range for a given area, property owners do not qualify for the assistance programs regardless of whether they purchased the insurance or not. The total cost borne by provinces is unknown as of February 2020, but according to the Special Advisor's Independent Review of 2019 Ontario flooding, disaster costs for the province of Ontario needs to exceed $46.2 million in 2019 value based on the DFAA formula to qualify for federal funding, and Ontario has not crossed this threshold as of October 2019 for either 2017 or the 2019 floods (McNeil, 2019).

After the 2019 event, the Quebec government introduced a special program by capping the FADV flood damage compensation at CAD $100,000 but offering up to CAD $200,000 for voluntary buyouts to homeowners in some regions to encourage them to leave their flood-prone homes and move to higher ground (Porter, 2019; Securite Publique Quebec, n.d.). This program is currently open for submission of compensation claims, and hence, information on total compensation paid is not available as of April 2019. The most recent estimate reported in media for 2017 floods is CAD $135 million paid to flood victims, compared to $20-$28 million average in a normal year, quoting the Minster of Securite Publique Quebec (CTV Montreal, 2018). The most recent estimate for financial assistance paid for 2019 flooding by Quebec is CAD $25.9 million as of June 2019 (Montreal Gazette, 2019). The Ontario government has not issued financial incentives beyond disaster recovery assistance for either the 2017 or 2019 flood event, but the province has been prioritizing stakeholder engagement to better plan for flooding and reduce its impacts. In response to the 2019 flood event that increased government and public concerns over the rising frequency of flooding in Ottawa River and surrounding areas, the Ministry of Natural Resources and Forestry appointed a Special Advisor on Flooding to review the province's flood management framework (McNeil, 2019; Government of Ontario, 2019). In addition, the Province of Ontario created an internal task force for flooding and held Flooding Engagement Sessions in Muskoka, Pembroke, and Ottawa to consult with municipalities, Indigenous, and industry leaders on improving flood risk mitigation and response (Government of Ontario, 2019).

Event comparison in respect to riverine flood hazard

During the winter, most of the precipitation received over the Ottawa River Basin is stored as ice or snow, and hence, the soil is still saturated in the spring when the snow in the ground is still frozen. In the spring of 2017, record levels of precipitation (257 mm as opposed to 150 mm April-May average between years 1981-2010) was received over the Ottawa River basin (ORRPB, 2018) [Figure 1]. The heavy rainfall on snow-covered and saturated soils, therefore, increased freshet and runoff into streams and low-lying areas, leading to widespread flooding in various regions from Chats Lake down to the Montreal Region between 5th April and 8th May. Similarly, in 2019, precipitation in April-May was above-average, although it was not as high and localized as precipitation in 2017. Temperatures also remained low throughout April 2019; hence, the snowpack did not reduce early in April as usual, remained twice the normal average amount for mid-April (ORRPB, 2019) and the upper portions of the basin contained 150-188% of the normal snow water equivalent for this time of the year (McNeil, 2019). The 2019 flooding occurred in two waves along with heavy rainfall events and snowmelt, causing flooding in various regions in Ontario, Quebec, and New Brunswick. Total precipitation for April-May of 2019 was lower and more distributed than that of 2017 [Figure 1 & 2], but mean discharge for May at the outlet of Ottawa River in Carillon in 2019 exceeded that of 2017 due to snowmelt freshet increasing later than normal in Spring 2019 [Figure 3] (ORRPB, 2019).

The Ottawa River Regulating Committee manages 13 principal reservoirs of the Ottawa River Basin to reduce exceptionally high peak flows in spring and minimize damage to the floodplain. These reservoirs are typically emptied between mid-December and March to make room for spring flows, but the streams flows during these two flooding events exceeded the capacity of the reservoirs (ORRPB, 2019). There are dams in the central and southern sections of the Ottawa River, but since these are run-of-river facilities, they have minimal ability to provide flood protection downstream (ORRPB, 2019). While structural failures were not reported within the basin, a natural dike failure occurred at Deux Montagnes lake (located at the outlet of Ottawa River Basin, northwest of Montreal), forcing 5,000 residents to evacuate without notice on April 27th of 2019 (Lowrie, 2019).

There have been no operational or structural adjustments made to the reservoirs after the 2017 or the 2019 flood event to the authors' knowledge (as of April 2019). According to the Ottawa River Regulation Planning Board (ORRPB), reservoir management decisions taken at principal reservoirs in 2017 reduced flow peaks downstream compared to natural discharges that would have occurred without the presence of the reservoirs (ORRPB, 2018). In fact, the independent review conducted by the Special Advisor on Flooding to review the province's flood management framework concluded that measures and decisions taken by water managers and control structure operators during the 2019 flood "were effective in reducing the magnitude of flooding and associated damages throughout the basin" (McNeil, 2019).

Figure 1: Accumulated Precipitation in Ottawa River Basin for April-May of 2017 (Source: Agriculture and Agri-Food Canada, n.d.)

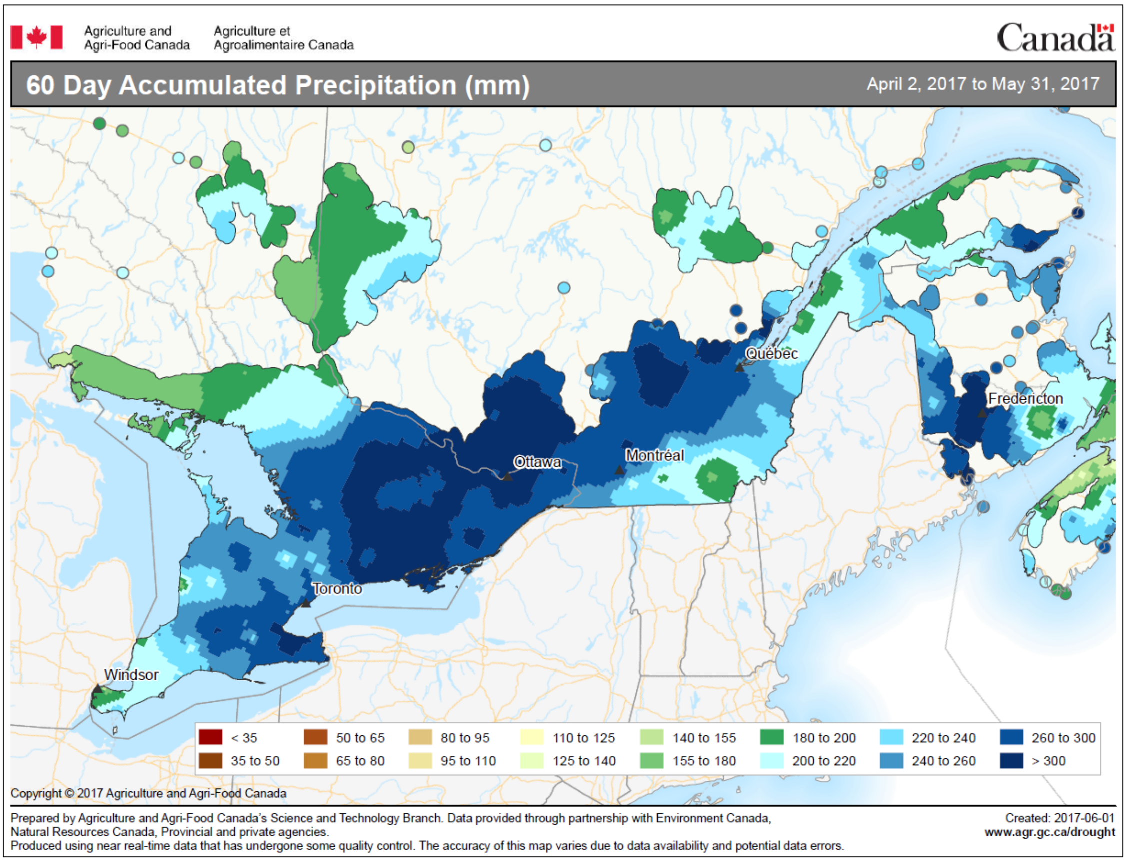


Figure 2: Accumulated Precipitation in Ottawa River Basin for April-May of 2019 (Source: Agriculture and Agri-Food Canada, n.d.)

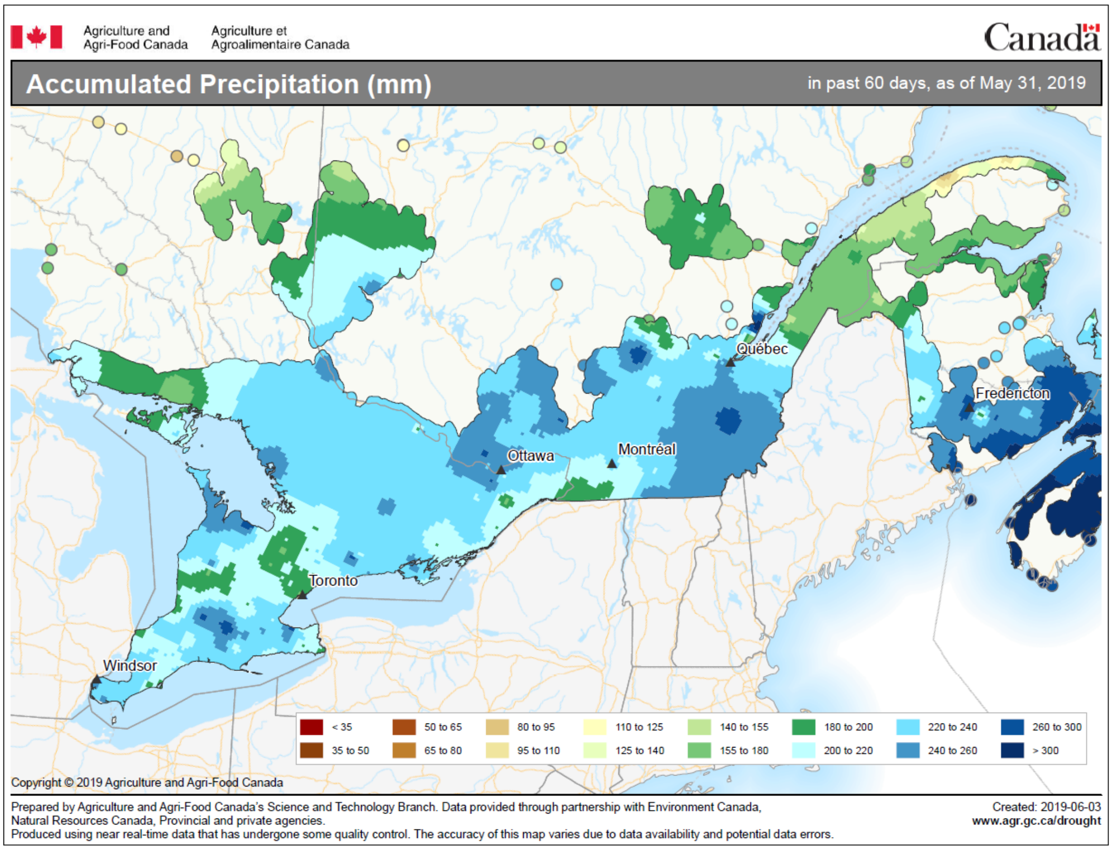
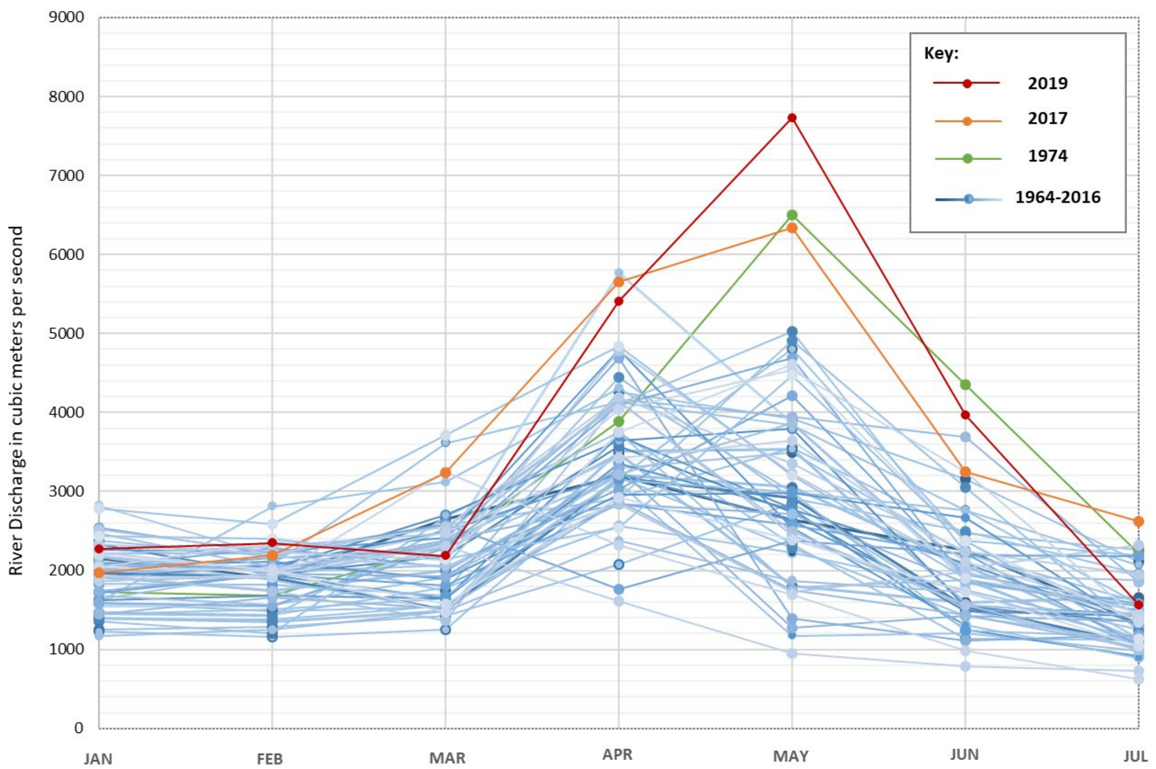


Figure 3: Mean Monthly Discharge, Ottawa River at Carillon (Data source: ORRPB, n.d.)



Event comparison in respect to exposure

The Ottawa River Basin covers an area of 146,300 km^2 with the 1,130 km long Ottawa River flowing along the boundary between the provinces of Ontario (35% of basin) and Quebec (65% of basin) (Ottawa River Institute, n.d.). The Ottawa River basin houses approximately two million people with most of the population concentrated along the main stem of the Ottawa River (ECCC, 2019) [see Appendix A]. Both flooding events occurred in regions along the Ottawa River and its downstream tributaries, exposing population centers, infrastructure, roads and farmlands situated close to water. The 2017 flooding is documented to have affected 286 municipalities in the province of Quebec (Teufel et al., 2019). Dozens of municipalities in Ontario are reported to have been affected by the 2017 floods but an exact number of municipalities flooded have not been reported by relevant authorities or in media to the authors' knowledge. The 2019 flooding event subsequently was reported to have affected at least the 23 municipalities and one First Nation (Indigenous community) that all declared states of emergency in Ontario (McNeil, 2019), and 250 municipalities are reported to have been affected in Quebec in 2019 (Montreal Gazette, 2019).

The 2017 spring flooding is reported to have affected or destroyed 6,171 homes in Ontario and Quebec, resulting in the evacuation of over 4000 people (Perreaux, 2018; Teufel et al., 2019). In 2019, the dike failure in Quebec brought the total number of flooded homes to 5,996, forcing an estimated total of more than 7,566 residents to evacuate (Statistics Canada, 2019; Floodlist News, 2019; The Globe & Mail, 2019; Lowrie, 2019; Press 2019b). However, because these numbers have mostly been reported in the news, there is low consistency in numbers quoted from various authorities and news sources. Since there are no cumulative impact studies for total area, assets or population exposed for either flood event yet, the credibility of data is limited. But since the dike failure in the Quebec portion of the basin did lead to more evacuations, the reported numbers indicate a slight increase in exposure due to the 2019 flooding event as compared to the 2017 flooding.

Event comparison in respect to vulnerability

After the 2017 floods, the Ottawa River Regulation Planning Board (ORRPB) undertook several initiatives regarding communications and access to flow forecast information. For example, the Board consulted provincial agencies and as a result, has undertaken a revamping of its website to provide better access to public about river flow conditions during extreme events (ORRPB, 2019). However, this revamped website was not published before the 2019 flooding happened. Several other organizations' websites, such as the City of Ottawa and Ottawa Riverkeeper, etc., now have information on volunteering opportunities and instructions on mitigating flood impacts such as safe use and disposal of sandbags (City of Ottawa, n.d.; Ottawa Riverkeeper, 2019).

As a consequence of the 2017 flooding, various other authorities took initiatives to address their lack of preparedness as well. For example, the City of Ottawa made use of a new mapping tool during the 2019 flooding that uses topographic LIDAR (light detection and ranging) maps to identify vulnerable infrastructure and make informed decisions with the use of resources to protect weak spots (Kupfer, 2019). The use of this mapping tool is reported to have helped guide emergency management strategies for the 2019 flooding event, e.g. by directing the military on making informed decisions regarding placement of sandbags in various areas of the city (Kupfer, 2019). Considering that this tool was proven useful in 2019, the city is working on making this program available to the general public (ibid); albeit, the timeline of implementation for this initiative has not been announced yet. Post the 2019 flooding, Hydro-Quebec has also added new technology to allow for real-time assessment of the rate of northern snowmelt to help with forecasting (Pfeffer, 2019). Similarly, the Ministry of Natural Resources and Forestry's Surface Water Monitoring Centre website launched a new web page after the 2019 flood that provides early flood warning messages to citizens (Ontario Ministry of Natural Resource and Forestry, 2019).

Organizational emergency management was similar in the case of both events. In both cases, the Canadian Armed Forces were deployed to assist residents in flooded areas, and disaster recovery assistance was activated by provinces of Ontario and Quebec to residents in affected municipalities. On the other hand, one particular management failure made flood impacts worse consistently for both flood events for the City of Ottawa, i.e. releasing untreated sewage into the Ottawa River due to the City's inability to deal with the amount of water passing through the sewage facilities. This is because sewage and stormwater sewer systems are combined in some older parts of Ottawa, and this combined untreated wastewater can overflow into the Ottawa River when overwhelmed by heavy rainfall or flooding (Martin, McKay, & Ballamingie, 2017). This untreated sewage overflow into the river has remained to be a problem with every heavy rainfall or flooding event, including in years 2017, 2018, and 2019. For example, the City of Ottawa released over 600-million liters of untreated sewage into the Ottawa River during the 2017 flooding (Martin, McKay, & Ballamingie, 2017). A Combined Sewage Storage Tunnel project was undertaken by the City of Ottawa in 2010 to store some of the sewage overflow; however, construction began much later in 2016 and the project construction was completed after the 2019 floods (Mes & Garber, 2019). Although the City is expecting it to be operational by 2020 (City of Ottawa, 2019), concerns over increasing flooding frequency are putting pressure on the city to put real-time warning systems in place for when untreated sewage is released into the river (Mes & Garber, 2019). There is no indication by the City of Ottawa yet on whether such warning systems will be introduced in the future or not.

Evidently, a number of different initiatives for increasing awareness and precaution, as well as improving preparedness and organizational emergency management were introduced after the 2017 flooding event. Even though the short time lag between the two flood events meant that they could not be fully implemented, the recognition that these improvements are needed for better flood risk and impact management suggests a slight decrease in vulnerability between the two flood events.

Summary

The primary adaptation effect can be observed in increased awareness and precaution due to major flooding experience only two years apart. Organizations and governments operating in the Ottawa River Basin at all levels are seeking to devise mechanisms to communicate flood risk and give early warning with improved forecasts of river conditions to the public. There is also indication in this case study of the evolving trend in organizational management strategies in Canada generally moving towards flood risk mitigation and prevention (as opposed to flood impact response and recovery that has been the norm). The level to which such initiatives have been or will be successful in flood risk mitigation is largely still in question since most of these measures are still pending implementation. Hence, it is not yet possible to conclude whether measures introduced or taken after the 2017 flooding had a measurable effect on reducing vulnerability to impacts of 2019 floods. An independent review of the 2019 floods in the Ottawa River basin indicated that river operations and management decisions did not have either positive or negative impact on flooding impacts, but instead, the volume of flow was significantly higher than the Ottawa River management system is designed to sustain, causing flooding in various regions (McNeil, 2019). A study investigating the mechanisms that caused the 2017 flooding event in the Ottawa River Basin also estimated that similar types of weather systems causing accumulated precipitation as high as that of 2017 are two to three times more likely to happen in present-day climate compared to pre-industrial climate (Teufel et al., 2019). The higher risk of flooding under climate change scenarios has indeed raised concerns in federal, provincial, and municipal governments, but guidance on how to integrate climate change considerations into technical guidelines used in flood risk management is lacking (McNeil, 2019). To put this in the context of Kreibich et al.'s (2017) paired event analysis framework, the 2017 flooding event is likely to have reduced vulnerability by increasing awareness and preparedness and highlighting the insufficiency of organizational management plans to account for a higher frequency or intensity of high-impact flood events in the Ottawa River Basin in a climate change context.

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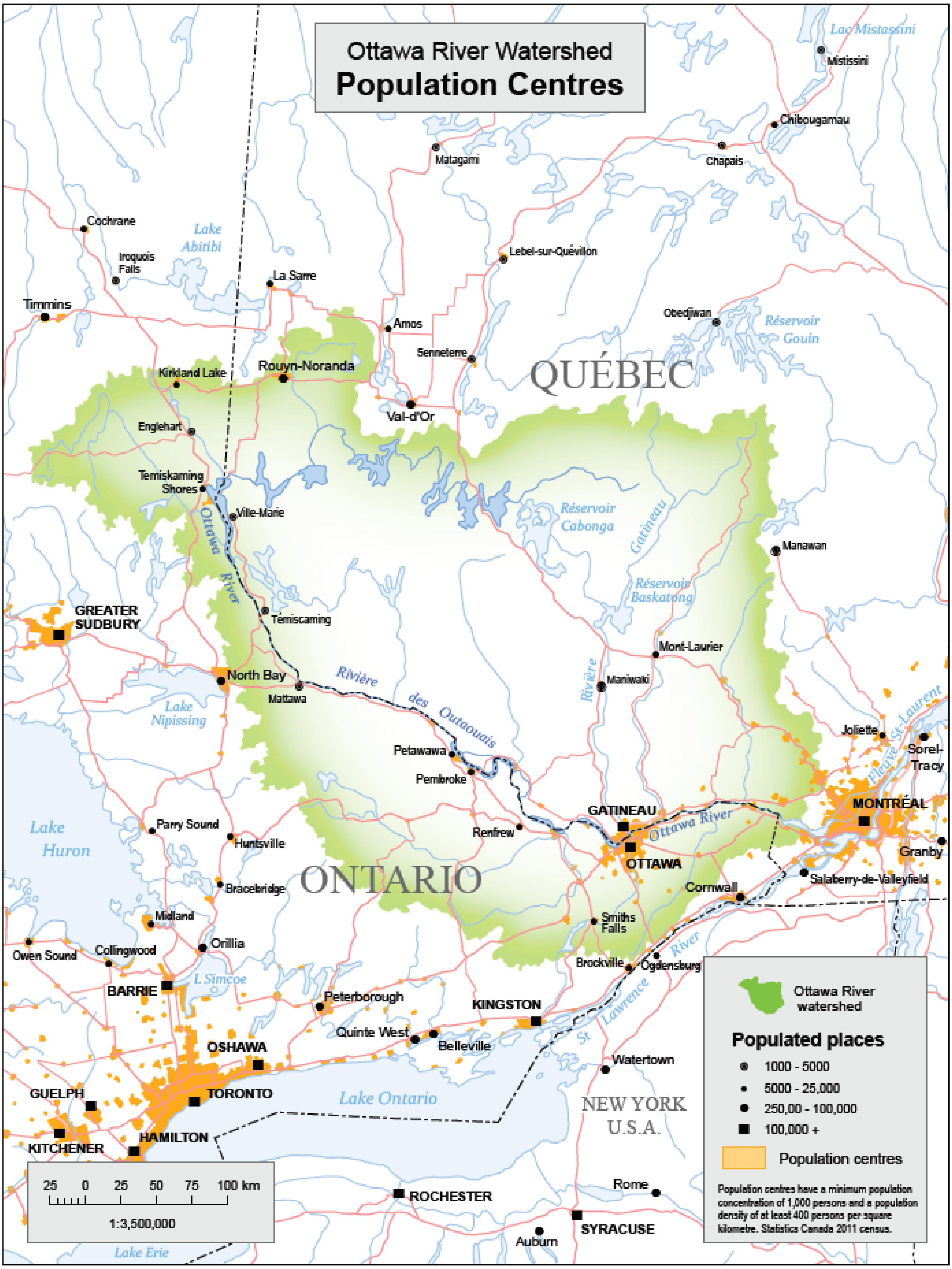
APPENDIX A: Ottawa River Watershed Population Centres (ECCC, 2019)



APPENDIX B: Ottawa River Watershed Management Agencies (ECCC, 2019)

ID 42

Paired flood events: 2004 and 2006 floods in the Delaware River Basin in the United States

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Short description of both events with a focus on impacts

The Mid-Atlantic Region of the United States experienced three major floods in September 2004, April 2005 and June 2006, over a period of less than two years (Smith et al., 2010). These events mostly affected the Mohawk River, Delaware River, and Susquehanna River Basins. Our focus here is in the events of 2004 and 2006 over the Delaware River Basin. The Delaware River Basin drains an overall area of 35,066 sq. km. This area occupies major parts of four different political states (Pennsylvania, New York, New Jersey and Delaware), and contains 42 counties, and 838 municipalities (Figure 1). The basin has experienced major flooding in past decades, including floods in 1955, 1973, 1986, 1996, 2004, 2005, 2006 and 2011.

In September 2004, heavy rain associated with the remnants of tropical depression Ivan produced widespread flooding in the Delaware River Basin during September 18-19. More than $1.2 million in federal disaster aid was distributed in the New York to assist with flood recovery by November 2004 (Brooks,2005). Six months later, in April 2005, a historic flooding event occurred on the main stem of the Delaware River as a result of snow melt and unusually high amounts of rain. Every county located along the main stem of the Delaware River was declared a Federal disaster area. Property damage estimates from the 2005 flood in Pennsylvania, New York, and New Jersey exceeded $200 million (Reed and Protz, 2007).

There is no any concrete documentation that other specific actions were taken for flood risk mitigation after the 2004 and 2005 floods. While the public were in the midst of recovery efforts from the 2004 and 2005 floods, the Delaware River was again subject to severe flooding in June 2006. Extremely heavy rainfall over the Delaware River Basin during the June 24-28 period caused flash flooding and record to near-record flood crests along many streams and rivers throughout the basin, including the main stem Delaware River. These were the worst floods on the Delaware River since the flood of record in 1955.

The flood of 2006 was blamed for four deaths across New York in the Delaware River Basin, and 3 deaths in the Susquehanna River Basin (Suro et al., 2009). These floods impacted different sectors, including business and residential properties, the transportation network, industry, public and private water supply, and wastewater treatment facilities. Recognizing that reducing flood loss is a responsibility shared by federal, interstate, state, and local governments throughout the region, the Delaware River Basin Interstate Flood Mitigation Task Force (DRBTF) was assembled later in October 2006 (DRBC, 2006). The goal with the task force is to develop a set of recommended measures for mitigating and alleviating flooding impacts along the Delaware and its tributaries.

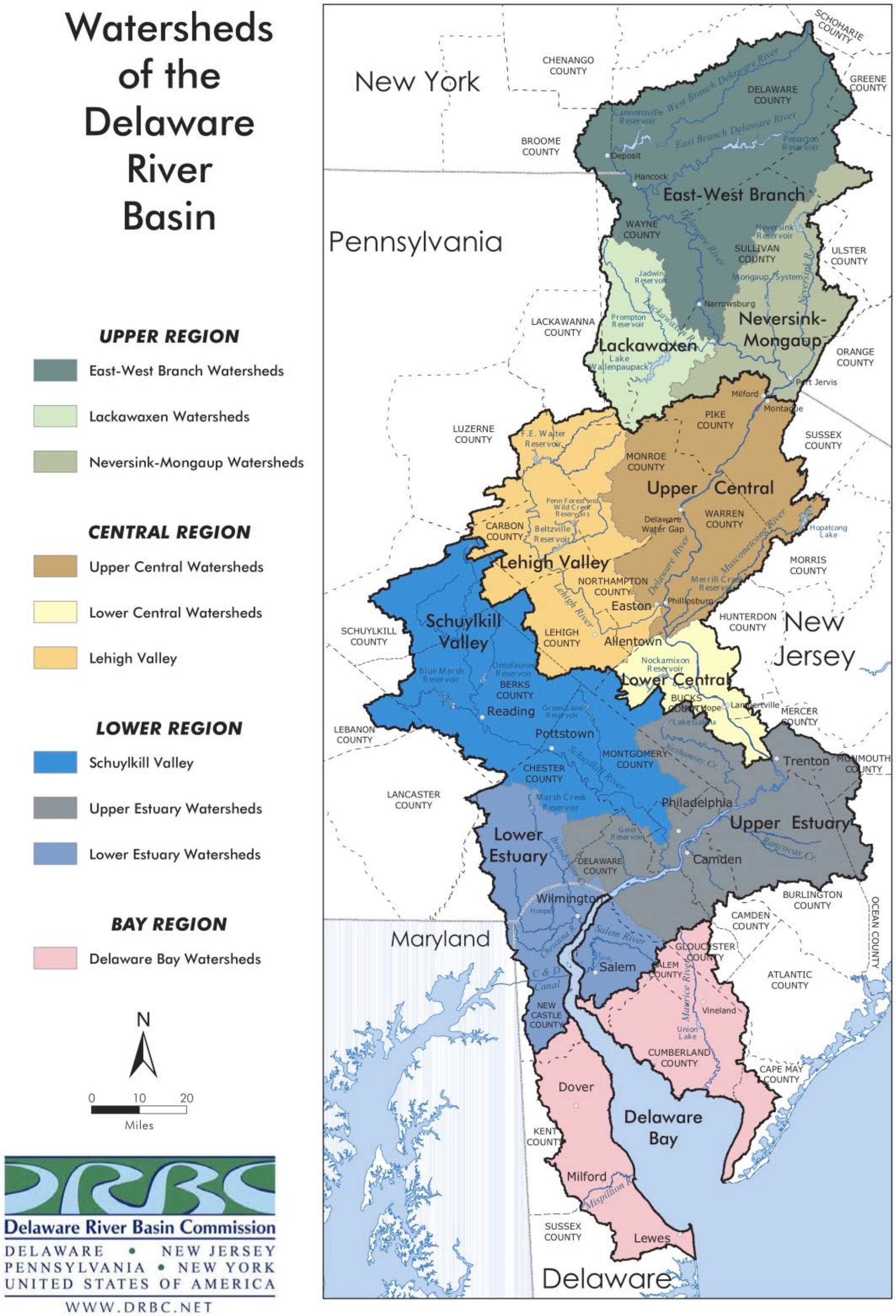
Watersheds of the Delaware River Basin
UPPER REGION
East-West Branch Watersheds
Lackawaxen Watersheds
Neversink-Mongaup Watersheds
CENTRAL REGION
Upper Central Watersheds
Lower Central Watersheds
Lehigh Valley
LOWER REGION
Schuylkill Valley
Upper Estuary Watersheds
Lower Estuary Watersheds
BAY REGION
Delaware Bay Watersheds
N
0 10 20
Miles
Delaware River Basin Commission
DELAWARE • NEW JERSEY
PENNSYLVANIA • NEW YORK
UNITED STATES OF AMERICA
WWW.DRBC.NET
New York
Pennsylvania
New Jersey
Maryland
Delaware
CHENANGO COUNTY
BROOME COUNTY
DELAWARE COUNTY
GREENE COUNTY
SCHOHARIE COUNTY
ULSTER COUNTY
SULLIVAN COUNTY
WAYNE COUNTY
LACKAWANNA COUNTY
ORANGE COUNTY
PIKE COUNTY
LUZERNE COUNTY
MONROE COUNTY
SUSSEX COUNTY
WARREN COUNTY
CARBON COUNTY
MORRIS COUNTY
NORTHAMPTON COUNTY
SCHUYLKILL COUNTY
LEHIGH COUNTY
HUNTERDON COUNTY
BERKS COUNTY
BUCKS COUNTY
MERCER COUNTY
LEBANON COUNTY
MONTGOMERY COUNTY
MONMOUTH COUNTY
CHESTER COUNTY
LANCASTER COUNTY
DELAWARE COUNTY
BURLINGTON COUNTY
CAMDEN COUNTY
OCEAN COUNTY
GLOUCESTER COUNTY
SALEM COUNTY
ATLANTIC COUNTY
NEW CASTLE COUNTY
CUMBERLAND COUNTY
CAPE MAY COUNTY
KENT COUNTY
SUSSEX COUNTY
East-West Branch
Lackawaxen
Neversink-Mongaup
Upper Central
Lehigh Valley
Schuylkill Valley
Lower Central
Upper Estuary
Lower Estuary
Delaware Bay
Deposit
Hancock
Narrowsburg
Port Jervis
Milford
Montague
Delaware Water Gap
Phillipsburg
Easton
Allentown
Reading
Pottstown
Trenton
Philadelphia
Camden
Wilmington
Salem
Vineland
Dover
Milford
Lewes
Cannonsville Reservoir
Pepacton Reservoir
West Branch Delaware River
East Branch Delaware River
Neversink Reservoir
Mongaup System
Jadwin Reservoir
Prompton Reservoir
Lake Wallenpaupack
F.E. Walter Reservoir
Penn Forest and Wild Creek Reservoirs
Beltzville Reservoir
Merrill Creek Reservoir
Hopatcong Lake
Nockamixon Reservoir
Blue Marsh Reservoir
Ontelaunee Reservoir
Green Lane Reservoir
Marsh Creek Reservoir
Union Lake
C & D Canal
Delaware River
Lehigh River
Schuylkill River
Salem River
Maurice River
Mispillion R.

Figure 1: Overview of the Delaware River Basin in the Mid-Atlantic Region of the United States (Source: The Delaware River Basin Commission: https://www.nj.gov/drbc/basin/map/ (last accessed July 2019). Credit: the Delaware River Basin Commission, www.drbc.gov.

Descriptions of processes between events with a focus on risk management

The floodplains within the Delaware River Basin are highly developed. During flood events, this can cause huge damages to business and residential properties, the transportation network, industry and utilities. For the flood event in 2004, NOAA's National Weather Service early warning system, the Advanced Hydrologic Prediction Service, provided decision relevant information that allowed for the necessary lead time to evacuate hundreds of people. During the flood of 2006, NOAA's National Weather Service flash flood warnings were in effect for nearly all counties in the Pennsylvania and New York portions of the Delaware River Basin. The NOAA's National Weather Service reported that the flooding was primarily the result of unusually heavy rain and/or snowmelt. However, other factors, including development, stormwater management, floodplain encroachment and reservoir management, have been pointed out by the public and/or larger scientific community as potential contributing and exacerbating factors.

Since three floods occurred within less than two years, effective flood mitigation plans were developed after the formation of the DRBTF in 2006. The DRBTF's plan for reducing flood damages includes recognizing event sequencing through implementing flood warning improvements, increasing federal funding for USGS stream and rain gages, complying with requirements for state and local hazard mitigation plans, updating floodplain maps in areas where development has occurred recently, strengthening floodplain regulations, maintaining flood control structures, and enforcing local storm water management regulations (DRBC, 2006).

Event comparison with respect to hazard

For the flood event in September 2004, the interaction between the remnants of tropical depression Ivan and a frontal boundary in the upper Delaware River basin produced more than 152.4 mm of rainfall over a 5-county area within a 24-hour period. The maximum recorded rainfall within the upper Delaware River basin in New York was 175.26 mm at Roscoe, Sullivan County. The rainfall intensity was very high, with a 50-to-100-year recurrence interval for a 24-hour storm. The flood peaks at the United States Geological Survey (USGS) stations on unregulated reaches in Beaver Kill at Cooks Falls New York (USGS gage station number-01420500) and Oquaga Creek at Deposit New York (01426000) had 90-year and 60-year recurrence intervals, respectively. New peaks-of-record at stations on the regulated reaches of the East Branch Delaware River at Downsville (01417000), Harvard (01417500) and above Read Creek at Fishs Eddy (01420980) equalled or exceeded a 100-year recurrence interval. These stations are downstream from the Pepacton Reservoir. The period-of-record maximum for the Downsville station, since the Pepacton Reservoir began storage operations in September 1954, is 572 m^3/s. Flood damage in New York was most pronounced in Delaware, Orange and Sullivan Counties.

For the flood event in June 2006, rainfall at some locations in the Delaware River Basin totalled more than 330.2 mm over a seven-day period. The probability of this rainfall over a seven-day period in the Upper Delaware is about 1 in 500 chance in any given year (NOAA Atlas 14). Heavy rainfall during June 24-26 saturated the ground and produced bank full and minor flooding conditions by early June 27. In addition, precipitation on June 27 and early on June 28 produced over 152.4 mm of rainfall across most of the counties in New York State. The recorded maximum precipitation was 339.34 mm in 24 hours at Walton New York (Suro et al., 2009). This caused record to near-record flood crests along many streams and rivers throughout the basin. The Beaver Kill at Cooks Falls stream-gaging station (01420500) recorded a new period-of-record maximum of 1766.97 m^3/s, which had a recurrence interval greater than 100 years. The USGS station at Downsville (01417000) and Harvard (01417500), which is largely controlled by the Pepacton Reservoir, recorded a peak discharge of 566.34 m^3/s and 625.80 m^3/s, which had 50- and 45- years recurrence interval, respectively. The USGS stream-gaging station at Fishs Eddy (01421000) also set a new period-of record maximum of 2191.72 m^3/s, which had a recurrence interval greater than 100 years.

One of the reactions to the floods of 2004-2006 was to blame the occurrence on increased runoff as a result of upstream development. However, the annual peak flows at different USGS gaging stations have not increased in magnitude over time, as would be expected from an increase in land development (Kucz, 2007). Next, the majority of flood victims blamed the three New York City Delaware Basin reservoirs – Cannonsville, Pepacton, and Neversink – as causes of flooding. The flood victims argued that the reservoirs were full prior to each of these floods, and that uncontrolled spills formed a component of downstream floodwaters. Although reservoirs were targeted as the causes of these floods, the historical flood data fails to support the arguments. Seven of the ten worst main stem floods in the Delaware River Basin recorded at Trenton over the past 100 years occurred in the absence of reservoirs or in the absence of spills (DRBTF, 2007). According to the USGS, reservoirs produce so little additional flow during flood events that the height increase in the Delaware is negligible (Kucz, 2007).

Event comparison with respect to exposure

The Delaware River Basin has substantial exposure to flood hazard. Of the population exposed, the most vulnerable include the economically disadvantaged and the population over the age of 65 (DMA, 2013). For the flood event in 2004, more than 1,000 people in the upper Delaware River basin were evacuated, and several hundred homes were flooded (Brooks, 2005). In Lehigh county, it was estimated that 85 homes, 31 businesses and 5 public buildings and structures were damaged (NCEMS, 2019). In Northampton County, 865 homes, businesses and structures were damaged, including several roads and bridges. Total damages for Lehigh and Northampton County were approximately $6 million. Preliminary reports indicate the total damage cost in Sullivan County alone was more than $10 million (Brooks ,2005). In New York alone, more than $1.2 million in federal disaster aid had been distributed to assist with flood recovery by November 2004 (Brooks,2005).

Based on a Hazards U.S. Multi-Hazard (HAZUS-MH) flood analysis, for a 1% flood event in Lehigh County, about 7281 people will be displaced, and 4,033 people will seek short-term sheltering, representing 2.3% and 1.3% of the County population, respectively (DMA, 2013). For a 1% flood event in Northampton County, about 7100 people will be displaced, and 3677 people will seek short-term sheltering, representing 2.7% and 1.4% of the County population, respectively. Critical facilities located in the 1% US Federal Emergency Management Agency (FEMA) flood zone in the Lehigh County include electric power, school, and airport. In Northampton County, critical facilities in the 1% flood zone include electric power, medical canter, shelter house, and police station. In Warren County, there are 1,096 buildings located in the 1% annual chance flood boundary, with approximately $276 million of building/contents exposed. In total, this represents approximately 2.3% of the County's general building stock inventory (approximately $11.9 billion). There are 1,566 buildings located in the 0.2-percent annual chance flood boundary with approximately $442 million of building/contents exposed. This represents approximately 3.7% of the County's total general building stock inventory (DMA, 2016).

Many of the communities that were exposed to major flooding during the September 2004 and April 2005 floods in the Delaware River Basin were flooded again during June 2006 (Suro et al., 2009). Twelve New York counties were declared Federal disaster areas, more than 15,500 residents applied for disaster assistance, and millions of dollars in damages resulted from the flooding. In Eastern Pennsylvania, over 5,000 homes, apartments and businesses were impacted from flooding (NCEMS, 2019). In Lehigh County, Pennsylvania, about 300 homes and businesses were affected, with losses of approximately $1 M in property damage and $1 M in crop damage. The Northampton County in Pennsylvania had approximately $10 M in property damage and $1 M in crop damage. Disaster-recovery assistance for individuals and businesses adversely affected by the floods of June 2006 reached more than $ 227 million (Suro et al., 2009).

Event comparison with respect to vulnerability

The Delaware River is vulnerable to major flooding. With three damaging floods in 2004-2006, the public feared that flooding of this magnitude will be frequent in the future because of floodplain encroachment, land development, reservoir management, among other factors. For the flood event in 2004, warning products and other tools from NOAA's National Weather Service, such as the Advanced Hydrologic Prediction Service, helped to provide the necessary lead time to evacuate hundreds of people. During the evening of June 27, 2006, NOAA's National Weather Service flash flood warnings were in effect for nearly all counties in the Pennsylvania and New York portions of the basin.

The number of repetitive loss properties in the basin prior to September 2004 was 209 (DRBTF, 2007). A property is considered a repetitive loss property by the FEMA when there are 2 or more losses reported which were paid for more than $1,000 for each loss. The 2 losses must be within 10 years of each other and be at least 10 days apart. Between September 2004 and February 2007, an additional 3,102 properties were added to this list. For total losses that occurred from January 1, 1978 through February 28, 2007, the US National Flood Insurance Program made flood loss reimbursements totalling over $318 million on a total of 3,311 repetitive loss properties within the Delaware River Basin (DRBTF, 2007).

According to the report on Delaware River Flood Mitigation prepared by the New Jersey Flood Mitigation Task Force on August 22, 2006, the existing floodplain mapping along the Delaware River was based on pre-1985 studies that underestimated the 100-year flood elevation, the floodways, and flood hazard areas for the 2004-2006 floods (NFMTF, 2006). The State's flood hazard area mapping greatly underestimated the limit of the floodway along the Delaware River. The State's flood hazard area mapping often underestimated the width of floodways along New Jersey's streams and rivers. Thus, the New Jersey Flood Mitigation Task Force recommended to develop new floodplain delineations and associated mapping with updated hydrology, verification of stage discharge curves, state of the art hydraulic modelling, and new delineations.

In October 2006, the Delaware River Basin Interstate Flood Mitigation Task Force was formed, in conjunction with NOAA's National Weather Service, USGS and US Army Corps of Engineers (DRBTF, 2007). The task identified several recommendations based upon a set of guiding principles concerning floodplain restoration, floodplain protection, institutional and individual preparedness, local stormwater management and engineering standards, and the use of structural and non-structural measures. The task force also identified deficiencies in the current warning system. The Task Force further found that recovery in the aftermath of the floods was hampered by inconsistent approaches by government agencies, uncertainty and gaps in relevant rules and regulations, and regulatory and bureaucratic barriers to appropriate reconstruction.

Summary

In September 2004, April 2005 and June 2006, three major floods caused devastation along the main stem of the Delaware River. These three floods reflect different principal flood-generating mechanisms in the eastern United States: tropical cyclones (September 2004); late winter–early spring extratropical systems (April 2005); and warm-season convective systems (June 2006). These were the worst floods to occur on the main stem since the flood of record in 1955. Nine lives were lost in these events, thousands of people were evacuated, roadways were closed, and many homes were damaged/lost as a result of these floods. The DRBTF was assembled in October 2006 to develop a set of recommended measures for mitigating and alleviating flooding impacts along the Delaware and its tributaries. The group has identified a total of forty-five consensus recommendations for a proactive, sustainable, and systematic approach to flood damage reduction. The recommendations are based upon a set of six guiding principles concerning floodplain restoration, floodplain protection, institutional and individual preparedness, local stormwater management and engineering standards, and the use of structural and non-structural measures.

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ID 43

Paired riverine flood events: 2009 and 2015 riverine floods in the Cumbria region in UK

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Short description of both events with a focus on impacts

The 2009 and 2015 flood events in Cumbria were characterized by exceptionally high rainfall, temperature and soil moisture. The impacts of the 2009 event were spatially heterogeneous whereas, the 2015 event is the biggest recorded flooding in Cumbria at almost all the river basins. The flood event of November 2009 is estimated to have caused an overall impact of £376 Million (£368 Million, corrected for deflation for the year 2015) (Wainwright and Morris, 2010), while the event of December 2015 (Storm Desmond) is estimated to have caused impacts between £520–£662 Million (Szönyi et al. 2016). Both the 2009 and 2015 floods significantly affected the infrastructure network in Cumbria. During the 2009 event, the collapse of a bridge in Northside killed a police officer who was directing traffic (System Risk ETN Flood Task Force Report, 2019). There were two casualties reported during the 2015 flood event (Burt et al. 2016).

Descriptions of processes between events with a focus on risk management

After the 2005 flood event (with a return period of 170 years), the flood defences in Carlisle, were improved to withstand a flood with a return period of 200 years. During the 2009 and 2012 events, the defences protected the region from flooding. However, since the 2015 event was much bigger, the flood defences were overtopped in multiple locations.

In other areas (like Keswick) flood defences were upgraded in 2011/2012 in response to severe flooding in November 2009 (McCall 2016a). Despite these improvements, the event of 2015 ended up being catastrophic for the community. The water levels in the river exceeded the designed height of the defences, which resulted in numerous overtoppings in the western and central part of Keswick (McCall, 2016a).

In Cockermouth, however, the flood of 2015 had lower water levels because of improvements to flood defences after the devastating 2009 event (McCall, 2016b). Some defenses were built to protect individual receptors (i.e. the police station), while others were installed along the bank of the Cocker River to protect adjacent roads and residential properties (McCall, 2016b). Additionally, the Cumbria City Council built a storage for excessive surface water below one of the streets of the town. Following the 2005 flooding, the government started a pilot for private precautionary measures in Appleby. About 45 properties received government funding to improve property level protection. These properties did not get impacted by the 2009 flooding, but the measures were ineffective in reducing the impacts of the 2015 floods.

Event comparison in respect to riverine flood hazard

Cumbria County experienced severe flooding in 2009 as a result of prolonged precipitation that took place from 19-20 November. The most affected catchment was the River Cocker catchment, within which the towns of Cockermouth and Workington were highly affected. Antecedent conditions may have played an important role as precipitation hit the region consistently in the previous months, leading to saturated soils and resulting in increased runoff (Environment Agency, 2012). In 2009, 316.4mm of rainfall was recorded over a 24-hour period on 19th and 20th of November (Environment Agency, 2012). In comparison, the meteorological winter of 2015/2016 was the wettest on record across all of the UK, with a precipitation of 341.4 mm, over a 24 hour period on 4th and 5th Dec (Szönyi et al., 2016). The December 2015 event broke numerous climate records causing damage from flooding and strong winds. The November 2009 event shows an overall lower monthly mean precipitation in comparison to the December 2015 event, with differences in the order of hundreds of mm of precipitation. Furthermore, during the December 2015 event, all of Cumbria was affected by heavy precipitation, whilst for the November 2009 event mostly the River Cocker catchment and to some extent the eastern part of River Carlisle catchment were affected by strong precipitation. The average precipitation for the flooding months of November 2009 and December 2015 are approximately 2.1 and 2.5 times higher as compared to the mean average precipitation in November and December (considering the years 1951-2018)(System Risk ETN Flood Task Force Report, 2019). The event in 2015 has a more widespread and generally higher antecedent soil moisture pattern as compared to the event in 2009. The mean soil moisture 3 days prior to the event is higher for the 2015 event (about 95%) as compared to the year 2009 (about 75%). The fact that the antecedent soil moisture was lower in 2009 may have contributed to the fact that the event in 2009 was less severe than in 2015. For the 2015 event at the Eden river in Sheepmount, located in the city of Carlisle, the estimated stage level was 7.6m. This value is around 30% higher than the stage level in 2009 (System Risk ETN Flood Task Force Report, 2019).

In 2009, up to 800 year return periods were observed in the Cocker and Derwent catchments causing severe flooding in Cockermouth and Keswick (Environment Agency, 2012). At Southwaite bridge on the river Cocker and several gauging stations on the Derwent, which both flow through Cockermouth, the return period was estimated to be higher than 200 years for the 2009 event (Miller et al., 2013). In 2015, up to 1000 year return periods were observed causing severe flooding in almost all catchments covering regions Carlisle, Keswick, Kendal and Cockermouth. (McCall, 2016 a,b). Return periods on the rivers Cocker and Derwent were estimated to be a 100 and more than 300 years, respectively (Environment Agency and Cumbria County Council, 2016). In Carlisle at Sheepmount the return period for the 2015 event was estimated to be 300 years (Cumbria Country Council, 2017).

For both events flooding was mainly caused by overtopping of defenses, because they were designed for return periods that were lower than the events in 2009 and 2015. There were no breaches of defenses in either of the two events (Environment Agency, 2012; McCall 2016 a,b).

Event comparison in respect to exposure

During the November 2009 event, 7,500 people (Cumbria Intelligence Observatory, 2010) and a total of 2,239 properties were affected. 1,794 of these properties were residential, whereas the rest were commercial. The most affected district was Allerdale (1,721), followed by South Lakeland (402), Eden (79), Copeland (22) and Carlisle (15). The total amount of commercial properties affected in Cumbria was 445. The affected properties were spread only across 3 out of Cumbria's 6 district areas: Allerdale, Eden and South Lakeland (Cumbria Intelligence Observatory, 2010). The town of Cockermouth, located in the Allerdale district, was heavily affected with relevant damages to infrastructures. In Workington and Barepot (Allerdale), the 2009 flooding affected the Forge Hammer court, the bowling and cricket club, the Cumbria constabulary, the Fusion nightclub, the Coopers Walk, the Ladies Walk Brewery and the Wilkinson's opera/bingo house building. In Pooley Bridge (Eden), 14 residential and 2 commercial properties were affected.

During the event, roads and bridges were severely damaged. Three very important road bridges were completely destroyed and due to evidence of structural damage, around 20 bridges were temporarily closed (Adger et al., 2016). In total, 244 bridges were blocked across the Lake District and other rural areas. Two road bridges and a key footbridge in Cockermouth were severely damaged by the flood waters. The Calva Bridge in Workington was closed and the Northside bridge and Navvies footbridge were demolished. A footbridge linking the banks of the River Derwent was destroyed. A policeman lost his life because of the collapse of the Northside Bridge. With the loss of relevant roads and bridges, the communities were unable to access medical services, schools and shopping areas, businesses operations were disrupted and employees were unable to reach their workplace. In some areas, power supplies and telecommunications (including emergency services) were interrupted (Cumbria Intelligence Observatory, 2010).

The 2015 event was overall more impactful than the event in 2009 regarding the amount of losses and the number of affected properties. 14,694 people were affected by the flooding and about 6,568 residential properties were affected in all of Cumbria (Flooding in Cumbria, Cumbria County Council Performance & Intelligence Team, 2018). In the village of Braithwaite (Allerdale), the local shop, hotel and pub were flooded, as well as the nearby A66 highway. In Wigton (Allerdale), a number of commercial businesses, including the Innovia Films Factory were affected. In Workington and Barepot (Allerdale), the cricket club, the bowling club and the Cumbria Constabulary West Area headquarters were flooded. In Kirkby Stephen (Eden), flooding caused the closure of the quarry and affected the Birkbeck Gardens, the station yard and the south road. In Pooley Bridge (Eden), flooding involved commercial and residential properties and the collapse of the bridge.

Event comparison in respect to vulnerability

In some places, like Carlisle, structural flood protection had been enhanced prior to the 2009 flood and was sufficient to prevent flooding from happening in these places in 2009. In other places, like Keswick, structural flood protection was improved after the 2009 event. Awareness of the risk and also the uptake of precautionary measures was still low in these places when flooding happened in 2015. This time structural protection was not sufficient to prevent flooding from happening, but awareness and preparedness was low among the population in these places. In the smaller cities or villages, that were less likely to have structural protection, the floods in 2009 that did cause flooding to happen, served to raise awareness and consequently the uptake of precautionary measures. Therefore, in smaller places the awareness and preparedness did increase in between the 2009 and 2015 events. (Defra/Environment Agency, 2009; Szönyi et al., 2016)

The environment agency provides flood warnings for at risk properties. This system was already in place prior to the 2009 event. During both events flood warnings were given and did reach some parts of the affected population, however the number of people receiving warnings is quite low and often warnings are received too late. (Flood task force report, 2019). Post 2009, the surface water maps were updated. In 2010, the Flood and Water Management Act was implemented which set up local flood authorities to decide on FRM strategies and then integrate them to form a national strategy for flood and coastal risk management in England (Surminski and Thieken, 2017).

In 2009, even though people and businesses were willing to help in the recovery planning, the offers to help were not coordinated on time (Fallon, 2011). In 2015, the impact of social media was crucial. Accounts such as 'Flood Alerts', 'DailyCumbria' and others from news agencies and relevant organizations such as Environment agencies, Council, Police and Emergency services provided relevant content to citizens such as safety warning, flood warning and updates. (Spielhofer et al. 2016).

There is no evidence of significant increase in the penetration of insurance between 2009 and 2015. However, in general flood insurance penetration is high in England (95% or more according to HM Government (2016) and Flood Re (2016)).

Summary

From a hydrological point of view the event in 2015 was more severe than in 2009. This also caused the impact to be more severe in 2015. There were a couple of larger cities and towns where awareness, the uptake of measures, and preparedness was low, due to the fact that structural protection had been increased and improved prior to this event (Szönyi et al. 2016). The structural defense system was not able to withstand the 2015 flood, however, and people got surprised by an event that they did not think could happen. Here we see a safe-development paradox, i.e. the people in Carlisle and other places felt safe due to the constructed defenses. On the other hand, Cockermouth did get flooded in 2009 and even though structural protection had been improved after that, they were aware of the risk, had taken private measures and were better prepared for the flood event in 2015. Also, smaller villages, where no structural protection schemes have been implemented, show an increase in awareness, the uptake of measures and preparedness in between 2009 and 2015 events. In these cases there is evidence of an adaptation effect.

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ID 44

Paired drought events: 2003-2004 and 2015-2018 droughts in the Cape Town region in South Africa

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Short description of both events with a focus on impacts

The city of Cape Town, South Africa, and its surrounding areas endured a prolonged meteorological drought (Figure 1) in the period 2015-2018 (4 years duration) (1-3). The drought escalated into a severe water crisis, also described by the media as 'Day Zero', which produced severe impacts and enormous costs (e.g. reduced water revenue, losses in agricultural production and drop in tourism) estimated around US$200 million (2). It caused about 35.000 job losses in agriculture and it is estimated that both the job losses and the food-price inflation have pushed about 50.000 people below poverty line (16). This event is contrasted with the previous persistent drought occurred in the area between 2003 and 2004 (2 years duration). The latter event was mild and had limited impacts on Cape Town metropolitan area (1-6).

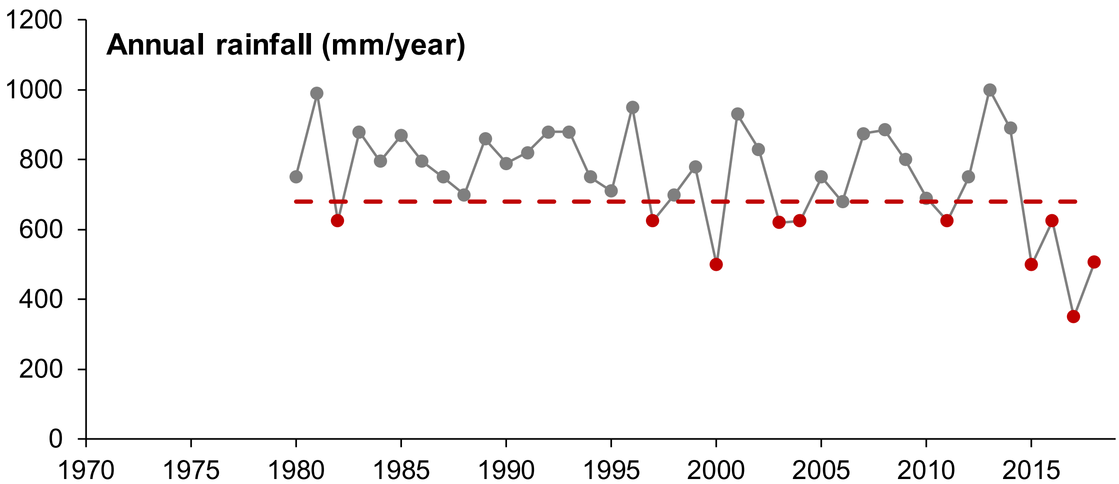

Figure 1. Total annual rainfall averaged over four rainfall stations of the Department of Water and Sanitation (1). We identified meteorological droughts as rainfall below a threshold equal to 680mm, i.e. long-term average (752mm) minus half the standard deviation (145/2 mm).

Descriptions of processes between events with a focus on risk management

Over the 10 years between the two events (2004-2015), a new reservoir was added to the water supply system of the city (Berg River Dam in 2009) whilst Cape Town population has increased from about 3.5 to about 4 million inhabitants. There have been efforts in managing water demands, but they did not entirely prevent increasing water consumptions (5).

In general, during low rainfall periods the National Department of Water and Sanitation (DWS) implements water restriction measures to reduce the amount of water allocated to different users. The level of restriction depends on the level of water storage in the Western Cape Water

Supply System WCWSS and the annual water demand (domestic and agricultural). Similarly, also the City of Cape Town can implement its own restrictions if needed.

The first event, i.e. the 2003-2004 drought, did not escalate into a severe water crisis. In 2004 the national Department of Water and Sanitation (DWS) foresaw only a 20% reduction (compared to the 2003 consumption) in water allocation for domestic uses. Concurrently, the City of Cape Town responded to this requirement with an official notice calling for Level 2 restrictions from 1 January 2005 implying about 20% of domestic water savings across the metropolitan area.

By contrast the second event, i.e. the 2015-2018 drought, mobilized national, local and international experts to manage the severe crisis, raise awareness and limit the drought impacts (9-12). The measures ranged from appointing a resilience task force, implementing water restrictions and tariff increases, using households flow regulators and carry out a relentless communication campaign which targeted both domestic and industrial users. The Day Zero campaign was quite effective amongst the City suburbs in limiting the per capita water consumption to 50 litres per day. DWS initially imposed 20% restrictions on both domestic and agriculture water use as early as May 2016. Agriculture water use restrictions were then increased to 30% in March 2017, 50% in October 2017, and 60% in December 2017. Domestic water use restrictions increased to 40% in October 2017 and to 45 % in December 2017. During the 2015-2017 drought, the City of Cape Town intensified the installation of flow restrictors or Water Management Devices (WMDs) in both high-income and low-income areas. This measure was aimed at controlling the amount of domestic water used and cutting the consumption if exceeding the maximum water allowed. In May 2017 the City Council appointed the Water Resilience Task Team (WRTT) with the aim of managing the crisis. Its main objective was identifying options for supplementing surface water. Businesses were also assisted through general or dedicated consultancies by the Provincial Government and other institutions to find alternatives for their water demands. The campaign did not target the formal and informal townships, which were instead assisted by NGOs or civil society organizations.

Event comparison in respect to drought hazard

In terms of meteorological drought, Wolski (1) analyzed rainfall data by averaging the values recorded by rain gages located across the catchment that supplies water to Cape Town metropolitan area. Figure 1 shows the total annual rainfall averaged over four Department of Water and Sanitation stations, and it highlights the exceptionality of the 2015-2018 drought conditions also relative to the 2003-04 event. In 2017, the maximum annual deficit was equal to 2.8 times the standard deviation from the long-term average, in 2003 it was only equal to 0.9 times the standard deviation from the long-term average (Figure 1).

Event comparison in respect to exposure

The metropolitan area of Cape Town includes over 40 towns with about 4 million inhabitants (4). Water supply relies heavily on a system of dams and reservoirs, which has grown over time (5). In accordance with the theory of supply-demand cycles (6), one can see that population has grown very fast after the storage capacity was increased in the late 1970s to early 1980s and more water was “secured” in the area. Between 2003 and 2004 about 3.5 million people were exposed to the drought, whilst during the 2015-2018 event the people exposed increased to about 4 million.

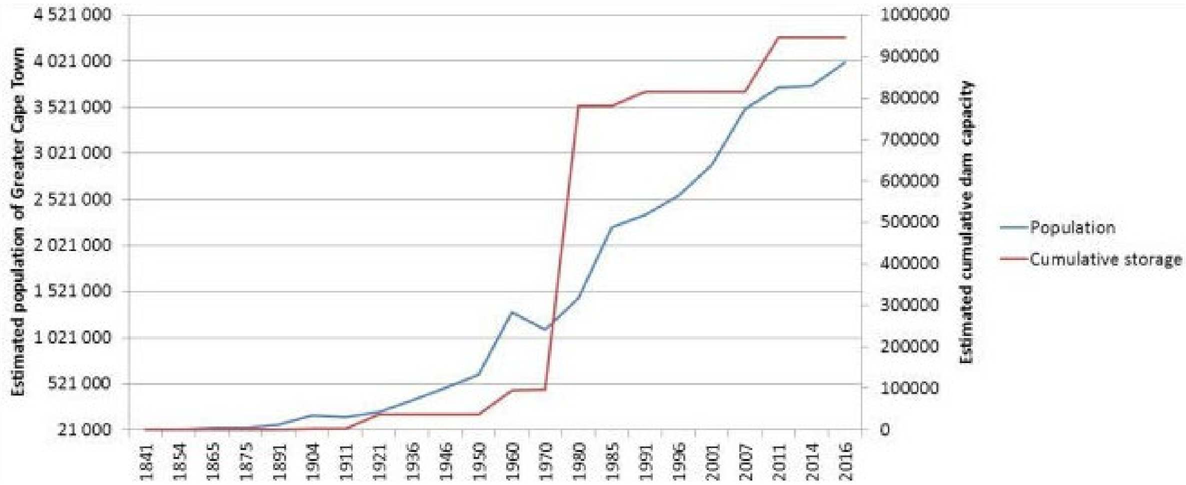

Figure 2. Population and water storage capacity (in megalitres) of greater Cape Town (Source: 5).

When performing the NDVI interannual variation between the two drought events, the second drought event results more severe in the impact it had on vegetation. In fact, if in the first case the NDVI difference ranges between 0.1 and 0.06, the values-range increases between 0.08 to 0.22 for the second event. The reduction of NDVI was thus far more significant after the recent drought. The 2015-17 drought was particularly severe for the cultivated land, and therefore for the local agricultural sector.

Table 1: Comparison of the NDVI analysis for the two drought events. (Source: own elaboration)

Land Classes	**Area %**	**2003-2004**	**2015-2017**	
		DIFFERENCE		
Wetland	3.09	0.08	0.17	-0.09
Forest	0.21	0.10	negl.	negl.
Dense Bush	8.60	0.07	0.10	-0.03
Open-Bush	1.91	0.06	0.10	-0.04
Grassland	6.10	0.08	0.15	-0.07
Low Shrubland	34.15	0.07	0.14	-0.07
Cultivated	16.65	0.06	0.22	-0.16
Forest Plantation	0.81	0.07	0.08	-0.01

The figures below are visual representations of the NDVI index across Cape Town metropolitan area before and after the two droughts events. The colour scale goes from light green to red as to exemplify high and low NDVI values. In both cases it is possible to observe a reduction of green area and an increase in yellow and red areas as a result of the reduction of NDVI index and the impacts that the two droughts had on cultivated and vegetated lands.

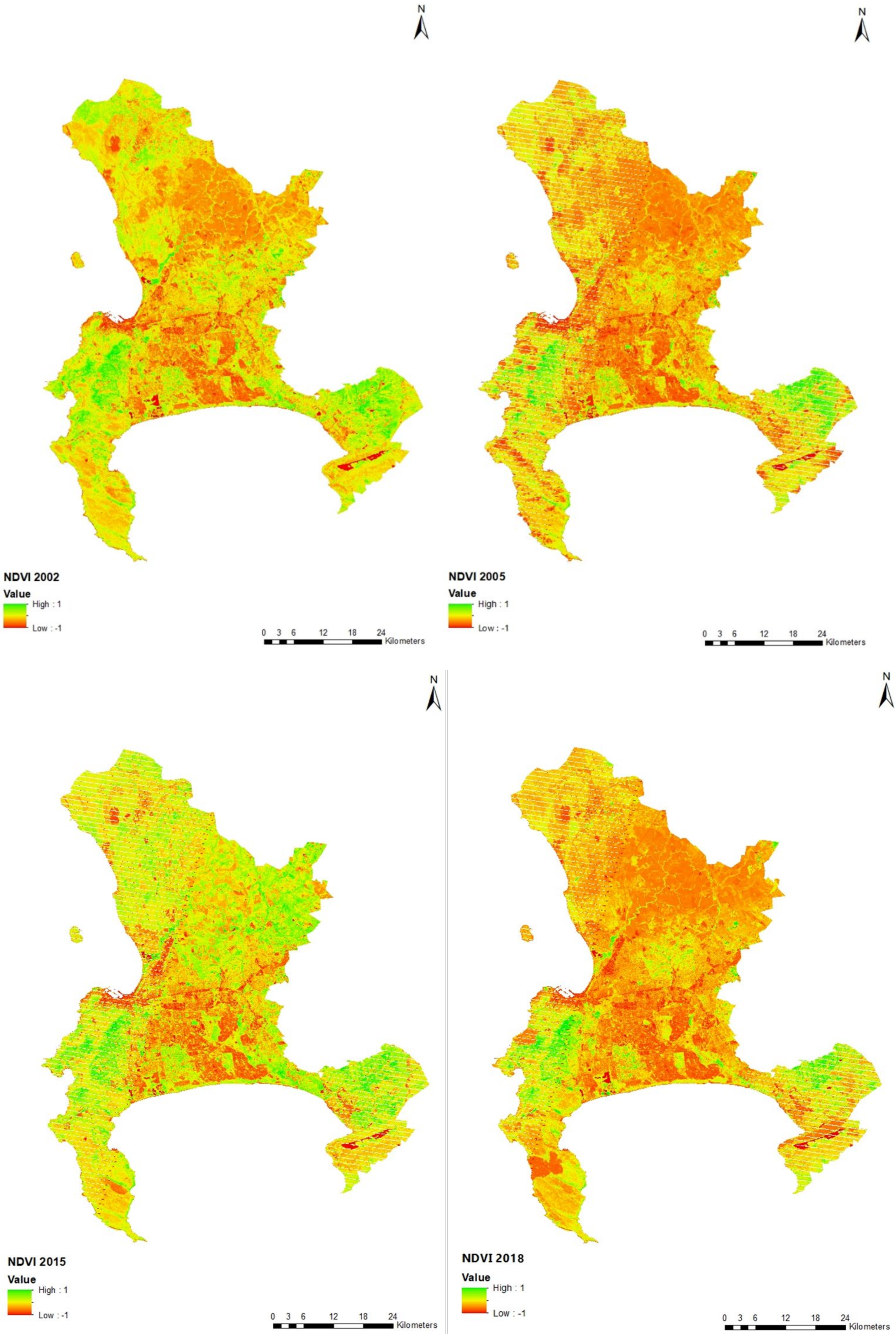

Figure 3: NDVI maps before and after the two drought events (Source: own elaboration)

Event comparison in respect to vulnerability

During the first drought event the government foresaw only an awareness campaign which started in October 2004 and mostly consisted of recurring requests to limit water uses for garden, cars washing and other irrigation systems. Overall these measures were not perceived as limiting or severe by the citizens. These restrictions only concerned the watering of gardens, lawns and public open spaces which was still allowed at night. The measures also prohibited the use of hosepipes for washing motor vehicles, motor boats, paths and paved areas and in turn, they limited the use of irrigation systems. In some cases, they included small raise in water and sanitation tariffs to ensure cost recovery and discourage high consumption patterns (7-8).

During the second drought event, the City launched numerous awareness campaigns through traditional and social media to raise people's awareness and assist people in reducing their water consumption, such as household leak detection and repair, together with advice on how to use 100 litres, then 87 litres in September 2017 and then 50l in early 2018. The main target of the campaign were the inhabitants of the City suburbs, yet not the informal settlements. When the crisis became more severe in November 2017, the private consultancy Resolve was appointed to strengthen the City communication campaign. Resolve pushed for the "Day Zero" name which made the City communication very visible and effective. In terms of preparedness, wealthier suburbs households bought rainwater tanks, bottled water or collected water from the closest springs. Where possible, they drilled private boreholes in their premises to become independent from the WCWSS (going off-the grid). In the formal townships, households usually collected water from the closest springs if available. In informal settlements, instead, families continued collecting their water in public standpoints (around 40 l/d/unit) and no other alternative was available.

Summary

The vulnerability of Cape Town to drought events has increased over the past decade as a result of the City heavy reliance on dams and reservoirs. Cape Town complex water supply system enabled economic growth and unsustainable water demand in an otherwise water-scarce area (4-6). In both cases although the droughts were triggered by meteorological events the overall impacts were mostly related to hydrological conditions. In fact, the City of Cape Town is almost solely reliant on surface water sources with little diversification from other sources.

The analysis of the paired events shows that the 2015-2018 meteorological drought was substantially more severe than the 2003-2004 event (Figure 1). Besides hazard, drought exposure was also higher as both population and water consumptions increased in the period between the two events (Figure 2).

One additional aspect that emerges in the Cape Town case is the uneven distribution of drought impacts. While in the wealthier City suburbs households had access to alternative water sources (rainwater tanks, bottled water, spring water, private borehole) and could pay the increased tariffs, the situation was harsher in the formal townships. There households could not afford higher tariffs or buy water from alternative sources. In informal settlements instead, families continued collecting their water in public standpoints (around 40 l/d/unit) and no other alternative was available.

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ID 45

Paired flood events: 2007, 2010, and 2014 pluvial floods in Malmö city, Sweden

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Since this report covers three events, it is identical to report of ID 27, please see pages 181-190.