Climate change, water-related disasters, flood control and rainfall forecasting: a case study of the São Francisco River, Brazil

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Abstract: Because of climate change, the frequency, intensity and/or duration of extreme weather events such as floods, droughts, storms and extreme temperatures is increasing. These events are often related to loss of property, money and life, especially in poor and developing countries where there is no or poor disaster management due to social and financial difficulties or due to a lack of synergy between the mitigation actions taken. Negative impacts can be reduced and losses can be better handled with proper water management techniques. However, these should not be handled solely with traditional management. The actual problem cannot be over simplified as merely a question of coping with resources availability and demand. Therefore, the present paper aims to summarize advances in weather forecasting and reservoir operation in the Upper São Francisco River, strategic to Brazil because it provides water to the semi-arid region and energy for economically thriving Brazilian regions. Moreover, it discusses challenges, opportunities and improvements needed to implement these advances in the current national integrated water resources management. This is mainly focused on water-related disaster mitigation.

Between 1990 and 2015, more than 1.6 million of deaths caused by natural disasters were recorded around the world. As this number continues to rise, regardless of recent progress on the implementation of disaster risk reduction strategies, stronger efforts are needed to build resilience and limit climate-related hazards and natural disasters. The full commitment of the parties and signatories of the Paris Agreement on Climate Change is required in order to mitigate climate change and its impacts (United Nations Economic and Social Council 2017). Water-related disasters (floods, windstorms, tidal wave and tsunami, droughts and water-borne epidemics) are the most frequent natural disaster, resulting in damage to property and loss of life. Among these disasters, floods and windstorms are the deadliest, accounting for 88.5% of the recorded deaths between 1900 and 2006. Even though water-related disaster fatalities are decreasing, their estimated economic loss is increasing, but both could be avoided with appropriate water-related management policies (Adikari & Yoshitani 2009).

As disasters resulting from extreme weather events (floods and droughts) pose severe negative social and economic threats to development and economic growth, managing the extremes in the

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hydrological cycle is critical to water resources management. Therefore, water-related disaster management should not be considered separately but part of integrated water resources management. In Gopalakrishnan (2013) current water disaster management policies are reviewed and five areas are identified to effectively meet future challenges: risk management, vulnerability assessment, capacity building and resilience, disaster risk reduction–development linkage and institutional design.

The 2015 World Conference on Disaster Reduction introduced the Sendai Framework, a result of lessons learned, which identified gaps from its predecessors (Yokohama Strategy and Hyogo Framework). This 15-year, voluntary, non-binding agreement recognizes the State as the main actor on disaster risk reduction, with shared responsibility with other stakeholders. It introduces innovations such as a strong emphasis on disaster risk management as opposed to disaster management. It also emphasizes tackling disaster risk reduction and climate-change adaptation when setting the Sustainable Development Goals, because the original Millennium Development Goals had an insufficient focus on risk reduction and resilience (United Nations 2015*b*).

Flood control techniques are important tools to reduce negative impacts and build resilience to destructive flash floods. These events result from intense and often brief rainfall events and from potential water scarcity driven by harsher drought. Improved weather forecasting coupled with a decision support system can be used as part of an early-warning system. It permits optimizing the storage capacity of a hydropower dam. Thus, predicting the occurrence of extreme weather events beforehand minimizes potential negative impacts. Besides that, apart from environmental obligations and flood protection purposes, water resources management allows other objectives to be met, such as water supply, navigation and hydroelectricity generation. In this study we demonstrate how in the Upper São Francisco River in Brazil, with the implementation of enhanced weather forecasting and a predictive control approach over a short-term forecast horizon, stress conditions or peak-flow events were able to be predicted and thus support decision-makers in taking action before these events happen so as to minimize their impacts.

Climate change, extreme weather and their implications to human development

Driven by natural and/or anthropogenic forces the climate is changing, that is both an increasing likelihood of occurrence and scale of extreme weather events (e.g. heatwaves, heavy precipitation and droughts). As this pattern worsens in the future, those events are likely to become more frequent and their consequences more significant (IPCC 2007; Marengo & Camargo 2008; Cubasch *et al.* 2013).

A recent report by the IPCC (2007) indicates that the occurrence and likelihood of extreme weather events is increasing. The return period of floods is likely to decrease as a result of changes in the peak runoff volume caused by changes in land use and land-cover, which will modify flood-hazard classification. Areas previously regarded as low hazard may become high-hazard zones (Hirabayashi *et al.* 2013; Zope *et al.* 2016).

As a result of long-term droughts, higher evapotranspiration and increased air temperature, future climate-change scenarios suggest that extreme events in large portions of South America will become more common, that could eventually lead to biome and vegetation changes, such as tropical forest savannization in Amazonia (Salazar *et al.* 2007; Hirabayashi *et al.* 2013; Magrin *et al.* 2014).

Extreme weather events can cause profound impacts on food production, economy, public health, energy production and transportation, and are responsible for a disproportionately large part of climate-related damage (Kunkel *et al.* 1999; Easterling *et al.* 2000; Meehl *et al.* 2000; Rosenzweig *et al.* 2001; Patz *et al.* 2005; Koetse & Rietveld 2009).

Financial impact and human loss caused by floods and water-related disasters

Although floods have beneficial impacts on the environment by fertilizing the river bank's soil, recharging ground water and performing an important role for ecosystems, these events can pose a threat to life, health, livelihoods and property. Floods are responsible for affecting the life of around 65 million people between 1972 and 1996 (Green *et al.* 2000; World Comission on Dams 2000). Adikari & Yoshitani (2009) suggest that basin management plans should be executed, rather than city or town plans, on the basis of an increased understanding of disaster trends and foresightedness. Even though it is difficult to evaluate precisely the economic losses, the estimated figures resulted from such events are often astronomical. According to the Swiss Re database of natural catastrophes, the estimated loss due to extreme natural events between 1977 and 2017 is USD4 trillion: USD2.9 trillion was caused by climate-related events (windstorm, flood, drought, hail and bushfire) and USD1.1 trillion caused by natural catastrophes (earthquake and tsunami). In the last decade (2007–2017) the average economic loss from natural disaster events is around USD171 billion each year (Holzheu & Turner 2018).

A recent study by Gopalakrishnan (2013), found that water-related disasters accounted for 90% of all natural disasters during the period 2000–2010. The study found that droughts, floods and storms together accounted for 60% of the fatalities (estimated at 1.07 million) and 96% of the victims (estimated at 2.48 billion) in terms of human losses. Water-related disasters also accounted for 76% of economic damage from all natural disasters, estimated at over USD1 trillion.

The estimated financial loss caused by natural disasters in the 1970s was USD75.5 billion, whereas the estimated loss during the period 2000–2008 was USD702.3 billion. According to Gokany (2009), the mortality rates and annual mortality due to extreme weather events has declined in the last two decades despite the increase of the probability of their occurrence and the population at risk, due to access to the capital and technology needed to prevent, protect and cope with any negative impacts. Therefore risk assessments are vital in identifying areas likely to be affected by such disasters, and even though flood protection structures are extremely expensive they can alleviate the financial impact and reduce the cost of rebuilding and reconstructing damaged areas (Jongman *et al.* 2014*a*, *b*).

Developing countries are especially vulnerable to impacts resulting from climate-change events. Their resilience is limited due to economic and social constraints, insufficient integration between different government administration levels (local, regional, national, etc.) and the inability of policy makers to understand the interconnections and synergies between climate-change management and other environmental and social benefits (Beg *et al.* 2002). In 2003, the estimated annual damage cost from natural disasters for developing countries was USD35 billion. To improve their ability to absorb the cost of disasters, these countries need to strengthen their adaptive capacity and incorporate economic and social impacts of extreme weather events analysis into their planning process (Mirza 2003).

Impacts and consequences of extreme weather events in Brazil

Even though Brazil possesses nearly one fifth of the world's water reserves, they are unevenly distributed (spatially and seasonally) throughout its territory. As climate dictates the water availability in Brazil, especially during the summer, any changes in the pattern and precipitation regime are likely to result in the occurrence of floods and droughts, with consequences for the agricultural and hydroelectric sector, resulting in impacts on both the economy and population. These alterations can directly affect river flows. Current studies indicate that the São Francisco River will drastically decrease its discharge as result of rainfall reduction, with severe consequences for irrigation and hydropower generation (Salazar *et al.* 2007; Nobre *et al.* 2016; Marengo *et al.* 2017*a*). Other factors that will aggravate water scarcity are environmental degradation, natural resources exploitation for economic growth and inadequate planning and management (Marengo *et al.* 2017*a*).

In Brazil, from 1994 to 2015 the estimated economic loss caused by water-related disasters was 182.7 billion Brazil ian Real (BRL). Floods and mudslides correspond to 40% of this sum and 39% of the registered disasters. For the same period droughts and frosts represent 54% of the estimated damage and 48% of the registered events (UFSC 2016*b*). In the last 30 years an analysis of the occurrence of high-intensity rainfalls and historic droughts shows that they have become more frequent; however, current weather models have uncertainties because of low resolution grids and physical-processes representation. Weather projections for South America indicate tendencies for increasing extremes in temperatures for the entire continent. It is projected that in Brazil, within the context of trends in extremes, there will be a reduction in rainfall in eastern Amazonia and the NE, and an increase in rainfall in southern Brazil (Marengo *et al.* 2009; Marengo 2014). A good example of this new dangerous trend is observed in Amazonia. This region, known for its vast water resources and watercourses, recently experienced successive severe droughts and floods events. The record flooding of 2009 was surpassed by the flood of 2012, and during the droughts of 2005 and 2010, the water levels dropped to such an extent that navigation along sections of the Madeira and Amazon Rivers was not possible. These were the most severe events in 45 years; moreover, the Brazilian Water Agency (*Agência Nacional de Águas* (ANA)), with data from the gauge station on the Negro River in Manaus, classifies these events as 'once-in-a-century' seasonal extremes (Marengo *et al.* 2013*a*).

Floods. In the last two decades severe flood events resulted in loss of life, evacuation of people and damage to property in different Brazilian regions (Table 1). The major examples of floods in Brazil are: the 2009 and 2012 floods of the Amazon River; the 2010 Santa Catarina State flood; the 2010 flood in the States of Alagoas and Pernambuco; the great flood of 2011 in Rio de Janeiro (World Bank 2012*a*, *b*, *c*, *d*; UFSC 2016*a*). Also, the Itajaí Valley located in the state of Santa Catarina in Southern Brazil was stricken repeatedly by flood events in 2008, 2011, 2013, 2014, 2015 and again in 2017. From 2005 to 2012, the Amazon Basin shifted from periods of extreme drought to record breaking

Table 1. *Recent extreme flood events in Brazil*

Year	Region	Estimated damage and impacted population
2008	Itajaí Valley (Santa Catarina)	Impacted at least 84 municipalities Affected 1.5 million people, 80 000 evacuees and at least 110 deaths BRL4.75 billion in damages
2009	Amazon River	USD165 million in damages (21 municipalities in Acre and Amazonas)
2010	Alagoas and Pernanbuco	BRL5.29 billion in damages (3.4 billion in Pernanbuco and 1.89 billion in Alagoas) 56 deaths (20 in Pernanbuco and 36 in Alagoas)
2011	Rio de Janeiro	BRL4.78 billion in damages 15 municipalities Affected 300 000 people with at least 905 deaths
2011	Santa Catarina	80 municipalities Affected 930 000 people At least 9 deaths BRL413,6 million
2012	Amazon River	Affected 29 000 people in Manaus and USD100 million damages in Acre
2013	Santa Catarina	Affected 20 000 people 72 municipalities
2014	Santa Catarina	Affected 47 000 people 44 municipalities
2015	Santa Catarina	Affected 31 000 people 99 municipalities BRL18 million in damages

floods. According to Tomasella *et al.* (2010) this extreme discharge fluctuation results from the side effects caused by alterations in the hydrodynamics of the basin rather than an excess or deficit of precipitation, making it vulnerable to abrupt weather pattern changes despite the sheer size of its rivers (Zeng *et al.* 2008; Tomasella *et al.* 2010).

In 2009 and 2012, the levels of the Solimões and Negro Rivers, branches of the Amazon River, rose resulting in floods in urban and rural areas along the Peruvian, Colombian and Bolivian Amazonia (Marengo *et al.* 2012; Espinoza *et al.* 2012; Marengo *et al.* 2013*a*). The 2009 flood impacted around 21 municipalities. The unpreparedness of the Civil Defence and the lack of resiliency resulted in a huge damage and cost: in the state of Amazonas alone, the housing-sector reconstruction costs were estimated at USD150 million and the estimated damages in the state of Acre were USD15 million (Marengo *et al.* 2013*a*).

Therefore, the consequences of the 2012 flood were considered more severe than those of the 2009 flood. Due to chronic underinvestment in small-scale agriculture and rural development, the poorest population in the Amazon Region could not cope with the negative effects. The city of Manaus had 16 neighbourhoods, touristic attractions, local business and the city centre and port facilities affected by the event and around 29 000 people were estimated to be impacted. This flood affected highways, roads and bridges, resulting in USD100 million of damages in the state of Acre (Marengo *et al.* 2013*a*).

The most destructive and deadliest among those, despite divergences in the official statistics, was the event in 2008. The Civil Defence damage report presents more conservative numbers, estimating around 1.5 million people being directly affected by the floods, the number of evacuees being in the order of 80 000, the number of damaged municipalities varying between 84 and 77, and the number of confirmed causalities varying between 110 and 135 (Sevegnani *et al.* 2009; World Bank 2012*d*; UFSC 2016*b*).

Even though some numbers are known, it is hard to make an accurate estimation of the total economic loss caused by the events in 2008. The estimations vary according to the source. According to a report from Comissão Técnica Tripartite Estadual de Meio Ambiente (2009) the infrastructure repair costs for bridges and roads were estimated at BRL360 million;

BRL194 million were required for the restoration of the City of Blumenau. More than USD340 million was the appraised loss resulted from shutting down the Itajaí Harbour during these events; and the emergency plan cost the Brazilian Federal Government more than USD400 million (Stevaux *et al.* 2009). The damage assessment made by the World Bank (2012*d*), indicates BRL4.75 billion: BRL1.46 billion for the infrastructure sector (transportation, telecommunications, water and sewage services and energy); BRL1.43 billion in damages to and loss of habitation; BRL155 million for public health; and BRL1.4 billion for the public sector (agriculture, industry and commerce).

In the following years (2011, 2013, 2014, 2017) the floods in the State of Santa Catarina and specially the Itajaí Valley received less public attention and were less documented compared to the 2008 event; the main sources were articles from the national and local press and local Civil Defence press releases.

In 2011 around 930 000 people in 80 municipalities were affected by another major flood event, which evicted more than 26 000 inhabitants from their homes and caused at least 5 casualties. A preliminary assessment estimated the losses at BRL413.6 million (G1 2011; Secretaria de Estado da Agricultura e Política Rural 2011). In 2013 the effects of extreme precipitation were felt by more than 20 000 people in 72 municipalities, most them located within the Itajaí Valley (G1 SC 2013).

The 2014 flood was felt in 44 municipalities affecting around 47 000 people damaging and closing 20 state and interstate roads (G1 SC 2014). In 2015 the flood impacted 97 municipalities and around 30 000 people. The municipal authority in Rio do Oeste estimated that 70% of the municipality was destroyed, causing an estimated loss of BRL18 million, the major losses being in the agricultural sector (BRL10 million) (G1 SC 2015; Silva 2015). According to data from the State of Santa Catarina Civil Defence reports, the most recent event in 2017 is estimated to have affected 99 municipalities and around 31 000 people. Even though the registered precipitation was higher than the event in 2008, there were no casualties due to the coordinated work of the Civil Defence and proper reservoir volume management (Defesa Civil de Santa Catarina 2017; Diário Catarinense 2017).

During June 2010, heavy precipitation caused floods in the State of Pernambuco and Alagoas, located in north-eastern Brazil. In Pernambuco 70% of the monthly expected precipitation (180 mm) occurred between the 18 and 19 June. Although a quick and organized response by the government and agencies avoided more serious consequences, damages and losses were around BRL3.4 billion, that represents 4% of Pernambuco's GDP. There were also 20 confirmed deaths as a result of flash floods in 77 municipalities (World Bank 2012*c*). In Alagoas the rainfall lasted from the 17 to 19 June affecting approximately 270 000 people, with 1131 injured and 36 deaths. About 8% of the GDP of Alagoas, BRL1.89 billion, are the appraised costs from material losses and damages (World Bank 2012*b*).

Regarded as the deadliest water-related disaster in Brazilian history, the 2011 disaster in the Rio de Janeiro highlands region was triggered by torrential rain, from the 11 to 16 January 2011. Of the 15 municipalities, that resultant floods and mudslides were felt in seven municipalities, affecting around 300 000 people (42% of the region's population), resulting in 662 people missing, 36 083 evacuated and between 905 and 910 dead (Ministério do Meio Ambiente 2011; World Bank 2012*d*).

The total estimated cost for loss and damage from this deadly disaster is around BRL4.78 billion, 40% of the Rio de Janeiro State GDP in 2009. About BRL2.2 billion (46%) are related to direct damages and losses and about BRL2.6 billion to indirect damages and costs. The damage to and loss of property of the transportation infrastructure was estimated at BRL621 million; BRL457 million for sanitation services; BRL214 million for the agricultural sector; BRL153.4 million for industry; and BRL469.2 million for commerce and services (Ministério do Meio Ambiente 2011; World Bank 2012*d*).

Droughts. Although droughts obey a different dynamic and pattern, they can be as potentially devastating as those caused from floods. The damage and loss resulting from long-lasting droughts result in deep consequences for agriculture, hydropower generation and human consumption. As this resource becomes more scarce, progress is hindered and latent water-use conflicts are exposed.

Brazil has also been affected by droughts, particularly in the north-eastern portion of the nation (Table 2). These two types of events might have a direct connection. A recent study indicated an essential correlation between the droughts of the austral summer of 2014, which resulted in the 'Water Crisis' in SE Brazil, with extreme rainfall events in western Amazonia. During the period of January 2014–2015 the rainfall over Acre in northern Brazil was intense in specific areas, 30.1 and 21% above average respectively for 2014 and 2015. On the other hand, in SE Brazil, the intense deficit of rainfall was 61.2% in 2014 and 63.2% in 2015 below average (Cavalcanti *et al.* 2017). From 2013 to 2015, SE Brazil, the most populated and economic active region of the country, struggled with the worst drought in 55 years, it resulted in impacts on water availability for human consumption, agriculture and hydropower production. Major Brazilian cities such as São Paulo, Rio de Janeiro and Belo Horizonte faced water

Table 2. *Recent extreme drought events in Brazil*

Year	Region	Estimated damage and impacted population
2005	Amazon Region	Impacted agricultural production Transportation Forest fires
2010	Amazon Region	62 000 families Outbreak of waterborne diseases USD13.5 million
2012 (ongoing)	NE Brazil	USD30 million in losses 11 000 municipalities
2014	SE Brazil	At least USD5 billion in losses Affected around 27 million people

shortages, affecting 40 million people (Coelho *et al.* 2016; Nobre *et al.* 2016). The so-called 'Water Crisis' was a direct result of below average precipitations between 2013 and 2014 combined with high-water demand because of the region's economic importance and population density, which ultimately resulted in extreme stress to the reservoirs in SE Brazil. The meteorological causes of this severe event are alterations to the regional atmospheric circulation during the rainy season over SE Brazil. The mid-troposphere blocking lasted 45 days and hindered the South Atlantic Convergence Zone. As a result, the austral summer of 2014 was one of the warmest and driest since 1951 (Getirana 2015; Marengo & Alves 2015; Marengo *et al.* 2015; Seth *et al.* 2015; Coelho *et al.* 2016; Nobre *et al.* 2016).

The drought of SE Brazil from 2013 to 2015 had a direct impact on the population as schools, businesses and even hospitals had their operations limited due to water shortage; some regions in the State of São Paulo needed water-trucks to supply water between 2014 and 2015. The prices of products increased up to 30% due to lower agricultural production during this period; and water and energy bills were also affected by a tariff adjustment during the height of the 'Water Crisis' (Nobre *et al.* 2016).

The estimated loss from this water crisis and its restrictions in the agricultural sector alone in 2014 is around BRL20 million: a 6.7% reduction compared to the sector's 2013 income (King *et al.* 2015; Nobre *et al.* 2016). According to insurance annual damage reports, the 'Water Crisis' in SE Brazil had an overall loss estimated at between USD3 and USD 5 billion, affecting more than 27 million people. One of the major loss events of the world in 2014 (Bevere *et al.* 2015; Jeworrek *et al.* 2015).

The Amazon Region located in northern Brazil, usually associated with its rainforest and large rivers, suffered a dramatic landscape change in 2005 and again in 2010. Espinoza *et al.* (2011) estimated that in 2010 the CO_2 release was around 8 billion tonnes and in 2005 around 5 billion tonnes, displacing the carbon absorbed by the rainforest. These extreme events, intercalated in a short period of time, are regarded as the worst droughts ever registered in that part of the nation resulting in great impacts on the population and ecosystems. Although droughts in the Amazon are thought to be rare and unusual, data from the Manaus gauge site on the Negro river, operating since 1902, indicates that these have become more severe and more frequent in the Amazon Region. The first recorded drought was in 1911, but since 1964 the magnitude of the droughts has increased and the interval between events has decreased: the events of 2005 and 2010 registered the lowest daily minimum since the beginning of recordings at the gauge site (Marengo *et al.* 2013*a*).

In 2005, because of low precipitation in the months that preceded the austral winter, the levels and discharges were at their lower point between May and July. The rainfall reduction continued during this dry period, approximately 25–40% less than average. These dry conditions caused fires in the Amazon (Marengo *et al.* 2008*b*). The 2005 drought caused negative impacts in several sectors including fisheries, transportation, health and agriculture. During this drought rivers, including the Madeira and upper and central Amazon River, became unnavigable. The water levels fell to extremely low levels, with communities only reachable by river transportation becoming isolated, hindering trade and commerce. As rivers dried up, the agricultural production decreased, impacting manioc and coffee crop production in 2006 and beans in 2005 (Marengo *et al.* 2008*b*; Anderson *et al.* 2011; Marengo *et al.* 2013*a*).

The 2005 cumulative number of fire outbreaks in Amazonia rainforest increased significantly, 33%

compared to the 1999 to 2005 mean; fires induced by drought were responsible by deforestation and biome transformation, releasing huge amounts of greenhouse gases (Marengo *et al.* 2008*a*; Marengo *et al.* 2008*b*). Data from the health service of Acre indicate an increase in hospital admissions and therefore cost, due to respiratory illness and waterborne diseases, that could be directly linked to soot from burnings and water-quality deterioration resulting from reduced flow volumes respectively (Marengo *et al.* 2008*b*; Tomasella *et al.* 2010).

Only five years after the 2005 event, the Amazon Region faced a more severe and longer dry spell. The 2010 drought affected large areas of the Amazon rainforest and water levels of major Amazon River tributaries set new record lows. Again, settlements reachable only by fluvial transportation became isolated because these local streams dried up. This drought resulted from El Niño effects during the austral summer and were intensified by the Tropical North Atlantic warming, which reduced humidity flux towards the Amazon Region. The result was the longest drought in 40 years and the lowest discharge ever registered in the Amazon River (8300 $m^3 s^{-1}$) (Espinoza *et al.* 2011; Lewis *et al.* 2011; Marengo *et al.* 2011; Espinoza *et al.* 2012).

The severity of this drought and their negative consequences on both fresh water supply and navigation is related to its longer duration. The combination of higher air temperatures, dry air and low water levels and discharge during the austral spring and winter increased forest fires by 200% (Marengo *et al.* 2011; Xu *et al.* 2011). According to local authorities and reports from government agencies around 62 000 families were affected by the 2010 drought The aftermath of the lack of proper sanitation and deteriorating water quality in rural regions were outbreaks of waterborne disease. The Brazilian government had to provide water pumping and treatment, food deliveries as an emergency measure, costing USD13.5 million (Lewis *et al.* 2011).

Unlike the last two examples in SE and north Brazil, NE Brazil is a region historically prone to drought: since the seventeenth century 45 drought events have been recorded. The War of Canudos, regarded as deadliest civil war in Brazilian history, can trace its origins in the social unrest and economic problems resulting from the droughts of 1896–1897. Due to the vulnerability and susceptibility to droughts of this region, since the 1950s the government has employed structural measures such as reservoirs and channels, as well as social programmes. The results are partially successful. Even though deaths caused by drought have not been registered since the 1970s, the population exodus from the semiarid region during droughts has not stopped (Marengo *et al.* 2013*b*).

The current ongoing drought can trace its beginnings back to the drought of 2012, having an intensity higher than the previous record holder that occurred in an El Niño year in 1998. Unusual warmer temperatures in the Tropical North Atlantic Ocean favoured an anomalous position of the Inter Tropical Convergence Zone. Thus, hindering rainfall in NE Brazil is believed to be the cause of the floods in Amazonia that year. Recent contradicting studies that associate La Niña with more precipitation between 2012 and 2013 in this region, did not alleviate the drought conditions (Marengo *et al.* 2013*b*; Marengo *et al.* 2016; Marengo *et al.* 2017*b*). This drought persisted in the following years with two peaks of higher intensity, from 2012 to 2013 and after the El Niño in 2015. Even though studies of the damage and loss are scarce, until 2017 this long event was estimated to have cost around USD30 million, affecting around 33.4 million people in more than 1100 municipalities. Of these municipalities, 997 declared a state of emergency due to severe drought, and social unrest was reported in rural areas (Marengo *et al.* 2016; Marengo *et al.* 2017*b*).

Investment by government to mitigate the impacts (special credit lines for small farmers and emergency water distribution by trucks) proved to be insufficient to cope with the impacts of this long drought. However, this crisis sparked the need for discussion and improvement. Efforts were made at Federal and State management level in order to handle the socio-economic and environmental problems caused by the event. Integrating scientific knowledge and technology of The Drought Monitor of the ANA with the Monitoring Program of Drought in Semiarid of the National Centre for Natural Disaster Monitoring and Alert (CEMADEN), it was possible to create indicators for drought monitoring and forecasting, and to be able to approach these issues with a focus on vulnerability reduction and resilience building (Marengo *et al.* 2017*b*).

Addressing weather uncertainty with weather forecasting techniques and early warning systems

The Brazilian energy sector is highly dependent on hydroelectricity: 68% of Brazil's electricity supply comes from hydroelectric power. In 2016 the total hydroelectric capacity installed was 96 925 MW, generating 380 911 GWh (Brasil Ministério de Minas e Energia & Empresa de Pesquisa Energética 2015). However, most of the installed capacity is concentrated in the south, SE and central-west regions of the country, making Brazil vulnerable to precipitation and hydrological pattern changes. An example of this was the severe drought of 2001 that resulted in blackouts and energy shortages. In the aftermath both the energy and the water resource sectors underwent restructuring, to improve planning, operation and management.

Whenever there is water scarcity, it is required to produce a larger than usual amount of electricity through thermal plants that burn fossil fuels to compensate for the reduction of production from hydropower sources. However, the energy generated by fossil fuels is more expensive and generates more greenhouse gas. During the 'Water Crisis' of 2014 in SE Brazil, the reservoirs supplying this power generation were almost dry. Hydropower dams were not able to provide enough energy and thermoelectric power stations were used to make up this shortfall in energy demand. This resulted in increased energy generation prices and tariffs in 2015 (Nobre *et al.* 2016). In contrast, artificial reservoirs can also be used as detention basins using their storage capacity to reduce the peak of downstream floods and related hazards (Green *et al.* 2000). Hence, reservoirs originally created to meet the needs of human activities such as irrigation, water supply, navigation, fish production, recreation and electricity production, arise as important players to mitigate environmental impacts of droughts and flood events. However, to operate these structures as efficiently as possible, non-structural measures may contribute significant value. This includes the monitoring of precipitation, river and reservoir stages as well as flow measurements, hydrological forecasting, early warning systems and the implementation of offline and online management strategies.

Climate variability, particularly over this vastly populated region of Brazil, has an important impact on governmental actions. Therefore, understanding the observed climate variability and explaining the causes of droughts in these regions is a fundamental strategic support for government decisions (Coelho *et al.* 2016). Understanding this variability itself is a challenge, and the scale of extreme events range from days to millennia. Moreover, when regarding weather uncertainty and weather forecasting, it is important to understand whether their likelihood and frequency is changing and to be able to better predict their severity and intensity.

Since the 1970s, driven by technological advancements in computational power, numerical models for weather simulation have been continuously enhanced and perfected. According to Marengo *et al.* (2009) and Bony *et al.* (2015), although current Global Climate Models (GCMs) allow better scientific understanding of anthropogenic global climate change, it is still required to obtain targeted projections of regional climate change. Current regional projections usually have coarse resolution and so limited skill and accuracy for local climate simulations. They are largely derived from GCMs, which are designed for different model skills and climate predictability. The development of regional climate-change projections is key to moving toward integrated assessment and skipping from mitigation to adaptation-based solutions for reducing vulnerability.

The use of hydrological models combined with precipitation forecasts is the main type of short-term runoff forecast generation for lead-times superior to the time of concentration of a basin. This enables operators to improve water storage management. Through this technique, operators can allocate additional storage before the flood event by pre-releasing water from a reservoir in order to mitigate damages at downstream rivers. It also prevents risks of dam structure over-topping and uncontrolled spillages. Furthermore, in case of droughts, optimized water-level management can help sustain water storage, avoiding drastic level dwindling and thus guaranteeing and optimizing water supply. For this purpose, a robust and fast routing model is required to obtain quick and reliable estimates of downstream flow conditions related to release changes from the reservoir (Kuwajima *et al.* 2014).

Usually in this kind of system, one source of rainfall forecasts is the standard (only one run of a meteorological model), resulting in only one possible trajectory for the future. This characterizes a deterministic runoff forecast. These deterministic hydrological forecasts quite often result in future runoffs that are very distinct from reality. The forecast system contains several uncertainties, such as imperfections in the hydrological and meteorological models or insufficient observed data (Taylor & Buizza 2003; Pappenberger *et al.* 2013). One of the main uncertainties in this procedure is the initial condition of the chosen meteorological model. Weather forecasting models are very sensitive to initial conditions of the atmosphere at the initial forecast calculation: slightly different initial conditions can result in a completely different state of the atmosphere (Lorenz 1969).

Even if the weather forecast numerical models were perfect, this dependence on the initial conditions would still exist and small errors in the estimation of the initial conditions could lead to significant errors in the forecast. To deal with this problem, the concept of ensemble forecast arose in meteorology. This technique allows for the exploration of uncertainties associated with the initial conditions and/or the structural deficiencies of the meteorological models (Georgakakos & Krzysztofowicz 2001). In an ensemble forecast, different meteorological models or different initial conditions of a single model are used to generate a forecast ensemble, where each of the forecast members represent a possible trajectory of atmospheric processes across the forecast horizon. Recently this incorporation of uncertainty concept by means of short-term ensemble forecasts has also been adopted in hydrology, particularly by applying ensemble forecast results of meteorological variables in a rainfall–runoff hydrological model to obtain, in the same way, an ensemble of runoff forecasts (Cloke & Pappenberger 2009).

Michaels (2015) acknowledges that advances in flood-risk estimation by implementing probabilistic weather forecasting techniques, notably ensemble prediction systems, have become components of decision making under uncertainty, in a landscape of evolving policy and advances in flood risk management. Compared to deterministic forecasts, these applications have demonstrated benefits in terms of forecast quality; a better understanding of the uncertainties associated with prognostics; better operational decisions; and, amongst others, motivating the development of several operational systems of hydrological ensemble forecasts around the world (Pagano *et al.* 2013; Pappenberger *et al.* 2013).

Brazilian hydropower operation and disaster risk management

In Brazil, the ONS (*Operador Nacional do Sistema Elétrico*) is responsible for the short-term and long-term operation of the Brazilian electric system and coordination of flood control. The ONS was created to manage the generation and distribution of electric energy. Because around 142 042 MW of the 150 338 MW of the Brazil's total installed capacity is currently interconnected to the SIN (*Sistema Interligado Nacional*), it is possible to transfer energy produced from one region to another (ONS 2009; EPE 2016, 2017).

This centralized coordination aims to optimize the SIN system as a whole and not each dam individually. For daily operations, ONS uses short-term forecasts (up to 15 days) to set the operation at each Hydropower Plant (HPP). If the forecasting systems are displaying situations of flood occurrence, the control of the dam is changed to the *in-situ* operator, to avoid safety-related problems (ONS 2009, 2016*b*, *c*, *d*, *f*).

The Operating Rules for Flood Control Policies are based on scenarios created using historical discharges and hydrological synthetic series, resulting in an offline guideline document containing a table describing different operating restrictions regarding different flood risk conditions (ONS 2016*a*, *b*) The flood risk conditions are divided into four categories regarding higher or lesser risk; maximum discharge violation; and allowed dam storage by the Operating Rules for Flood Control Policies. In a 'Normal' flood risk condition, there is no risk of a flood event nor violation of discharge or storage; the 'Attention' condition implies risk of a flood event or that the storage is full, but there is no indication of maximum discharge violation; the 'Alert' condition is characterized by a flood risk event while the storage is full and with indication of maximum discharge violation; and the 'Emergency' condition means that there is a flood risk event with full storage and maximum discharge violation. Aside from Normal and Attention conditions, operators have little or no operational freedom. The only situation when operators can set and decide target values for spillway and turbine discharge are under Alert and Emergency conditions (ONS 2016*a*).

Aside from ONS and hydropower operators there are other institutions with shared responsibilities on disaster risk reduction. Meteorological data and river monitoring data are provided by the *Companhia de Pesquisa de Recursos Minerais* (CPRM; Geological Survey of Brazil), *Instituto Nacional de Meteorologia* (INMET; National Institute of Meteorology), *Centro de Previsão de Tempo e Estudos Climáticos Studies* (CPTEC; Centre for Weather Forecasting and Climate), *Instituto Nacional de Pesquisas Espaciais* (INPE; National Institute for Space Research) and the ANA. The mitigation actions and planning are done by the *Ministério de Integração Nacional* (Ministry of National Integration) and its *Secretaria Nacional de Proteção* (National Secretary of Protection), *Defesa Civil* (Civil Defence), *Centro Nacional de Monitoramento e Alerta de Desastres Naturais* (CEMADEN; Centre for Monitoring and Alert of Natural Disasters) and *Centro Nacional de Gerenciamento de Riscos e Desastres* (CENAD; National Centre for Risk and Disaster Management).

The transition towards a probabilistic risk management requires further institutional capacity development and integration of actions between the several institutions involved in this subject (Thompson & Graham 1996; Pahl-Wostl 2007; Haasnoot *et al.* 2011). New developments for longer forecasting lead times, advances in decision making aids and inclusion of probabilistic forecasting in hazard mitigation need to be made to meet the different needs of both users and sectors.

Based on such a scenario, recent studies have looked at the performance of forecasting techniques in large tropical basins, such as the basins in the main Brazilian hydroelectric reservoirs, and the potential benefits they could offer in terms of quality and persistence of runoff forecasts for them. As examples, the studies of Fan *et al.* (2014, 2015*a*, *b*, *c*) showed the results of short-term hydrologic ensemble forecast evaluation for large basins in Brazil and concluded that, based on performance metrics, the use of ensembles have a series of advantages in comparison to single deterministic forecasts. Among the evaluated datasets, the ones produced from the ECMWF (European Centre for Medium Range Weather Forecasts) were featured. After these and others recent studies the ONS has started to include the use of short-term ensembles in its methodologies. Also, other very important HPPs, such as the Itaipu Dam, the largest Brazilian dam, have started to adopt hydrologic ensemble forecasting (Lisboa *et al.* 2015; Fan *et al.* 2017). As ensemble forecasting techniques become more accurate their use could be extended to higher lead time applications, where deterministic predictions have been traditionally applied in the last two decades. The use of persistence information from deterministic streamflow forecasts, as an uncertainty measurement for decision-making, appears to be an interesting strategy with advantages in medium-range lead times for anticipation of hydrological events compared to single deterministic forecasts (Fan *et al.* 2016).

Weather forecasting for operation optimization at the Três Marias HPP

Due to its location and significant size, the São Francisco River is one of the most important Brazilian rivers. It is the most important river of drought-prone NE Brazil and is strategic to the Government's important inter-basin water transfer project designed to increase water availability and mitigate the frequent droughts affecting the states of Ceará, Rio Grande do Norte, Paraíba and Pernambuco. The *Velho Chico*, as it is called by the locals, also has huge cultural significance. Its surrounding areas are filled of architectural, archaeological and heritage sites (Santos 2003).

Located in the Upper São Francisco River Region in the centre of the state of Minas Gerais between the municipalities of São Gonçalo do Abaeté, Felixlândia, Morada Nova de Minas, Biquinhas, Paineiras, Pompéu, Abaeté e Três Marias (Fig. 1), the Três Marias reservoir, also known as UHE Bernardo Mascarenhas, is one of the 9 reservoirs built for hydroelectric purposes on the São Francisco River (Três Marias, Sobradinho, Luiz Gonzaga (Itaparica), Apolônio Sales (Moxotó), Xingó, Paulo Afonso I, Paulo Afonso II and Paulo Afonso III).

The CVSF (*Comissão do Vale São Francisco*) started the dam construction in 1958. In 1962 at the time of its inauguration, the Três Marias Hydropower Dam was the biggest in Brazilian: 2700 m wide and 75 m heigh, with a gate-controlled spillway. The reservoir has maximum surface area of around 1090 km^2 and a maximum storage of 19 528 hm^3. With six 66 MW generators powered by Kaplan turbines, the total installed capacity is 396 MW. The dam is integrated into the SIN and is currently administrated by CEMIG (*Companhia Energética de Minas Gerais*) with operation coordination by the ONS.

The historical total daily release of the Três Marias dam from 1931 to 2011 ranged between 42 and 7245 $m^3\ s^{-1}$with an average discharge of

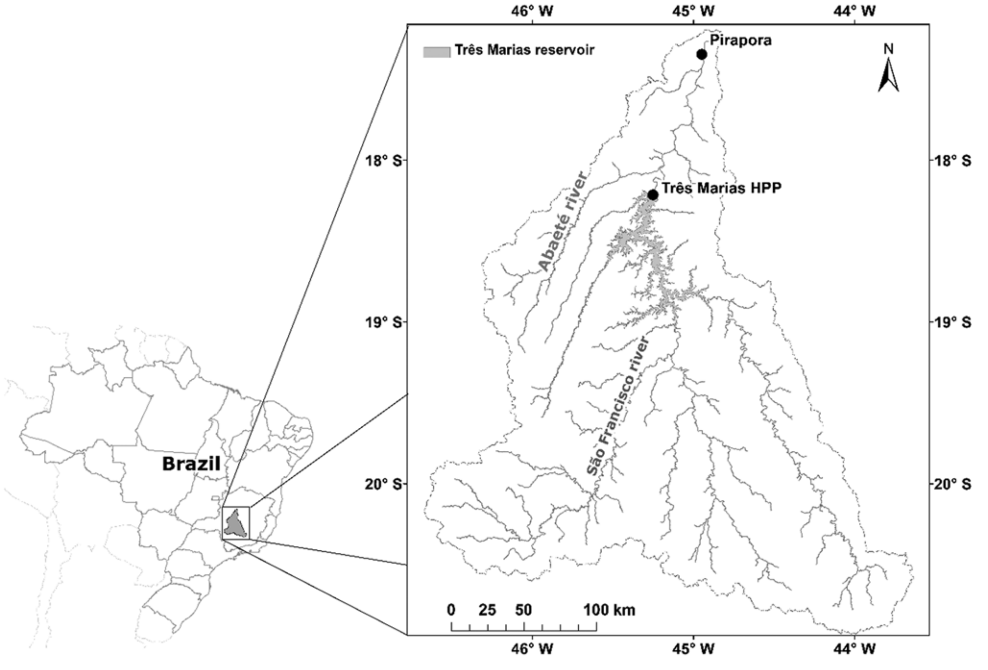

Fig. 1. Location of the Upper São Francisco Basin and Três Marias HPP.

689 $m^3 s^{-1}$. The dam's discharge prediction is relevant to the operational process of the subsequent downstream reservoirs at the São Francisco river, since it is responsible for about 26% of the total river discharge, and therefore significantly affects the northeast energy strategy (ONS 2009). The dam is important in the SIN operation and is regarded as strategic due to its scale, hydraulic and energetic relevance and its role in the network security. This implies that Três Marias is vital for grid stability and has impacts on the ONS centralized hydraulic operations and network security. Therefore, the ONS is responsible for scheduling the target values on a monthly, weekly, daily and real-time basis (ONS 2016*b*, *e*, 2017).

The dam must operate under several operational discharge restrictions regarding flooding downstream: discharges above 2000 $m^3 s^{-1}$ released at the reservoir will inundate islands populated by communities located downstream and discharges above 4000 $m^3 s^{-1}$ will cause severe floods in the city of Pirapora, located about 130 km from the dam. If the discharges of the dam and from the incremental basins reach the order of 8000 $m^3 s^{-1}$, the flooding inundation may extend to regions located in the state of Bahia at the middle and lower Sao Francisco basin, about 700 km away from the dam. The operational dam management is further limited by environmental restrictions. The discharge can only be reduced to values lower than 460 $m^3 s^{-1}$ after ichthyofauna monitoring to avoid fish detention. The same rule is applied to the spillway closing: a minimum discharge equal or greater than 420 $m^3 s^{-1}$ must be always ensured for environmental flow purposes. The flow variation should always be shifted slowly at the rate of 150 $m^3 s^{-1}$ per 30 min (ONS 2018*a*, *b*).

The Três Marias is a well-documented case researched by several authors regarding short-term forecasts at the dam. Moreover, all these studies used short-term ensemble forecasts to consider uncertainty.

Fan *et al.* (2014), showed experiments of ensemble forecasting applied to the HPP and the results showed some benefits in the use of ensembles, particularly for the reservoir inflow on flooding events, in comparison to the deterministic values given by the control member of the ensemble and by the ensemble mean. Despite the necessary improvements mentioned for the system, the results suggest that benefits can also result from the application of ensemble forecasts for hydropower plants with large basins within the Brazilian energy system. Fan *et al.* (2015*b*) undertook a verification of inflow into hydropower reservoirs using ensemble forecasts of the 'The International Grand Global Ensemble' (TIGGE) database for large-scale basins in Brazil, including the Três Marias Dam. The work presents one of the first extensive efforts to evaluate ensemble forecasts for large-scale basins in South America using TIGGE archive data. According to the authors, results from these evaluations confirm that ensemble forecasts depend on the particular model used to run the hydrological model and suggested the better performance of ECMWF model at the basin. These conclusions motivated the use of this particular weather forecasting model in the further studies conducted at the basin. In a continuation of the studies, Schwanenberg *et al.* (2015) demonstrated the development of state-of-the-art applications of a short-term reservoir management system, which integrate several advanced components, namely hydrological modelling and data assimilation techniques for predicting streamflow, optimization-based techniques for decision-making on the reservoir operation and the technical framework for integrating these components with data feeds from gauging networks, remote sensing data and meteorological weather predictions.

The basis for the anticipatory short-term management of the reservoir over a forecast horizon of up to 15 days are the streamflow predictions of the *Modelo de Grandes Bacias*, also known as the MGB hydrological model, first developed by Fan *et al.* (2014). This novel short-term optimization approach consisted of the reduction of the ensemble forecasts into scenario trees as an input of a multi-stage stochastic optimization. The authors showed that this approach has several advantages over commonly used deterministic methods which neglect forecast uncertainty in short-term decision-making. First, the probabilistic forecasts have longer forecast horizons that allow an earlier and therefore better anticipation of critical flood events. Second, the stochastic optimization leads to more robust decisions than deterministic procedures which consider only a single future trajectory. Third, the stochastic optimization permits an introduction of advanced chance constraints for refining the system operation. These same scenario optimization techniques were further developed and implemented by Naumann *et al.* (2015) to dams in the USA.

Closing the block of short-term ensemble forecasts for the Três Marias optimization, Fan *et al.* (2016) introduced a novel, mass conservative scenario tree reduction in combination with a detailed hindcasting and closed-loop control experiments, operating with two main objectives: (1) hydroelectricity generation and (2) flood control downstream. In the experiments, precipitation forecasts were based on observed data, and deterministic and probabilistic forecasts were used to generate streamflow forecasts in a hydrological model over a period of 2 years. According to the authors, results for a perfect forecast show the potential benefits of the online optimization and indicate a desired forecast lead time of 30 days. In comparison, the use of actual forecasts of up to 15 days shows the practical benefit of operational forecasts, where stochastic optimization (15 days lead time) outperforms the deterministic version (10 days lead time) significantly. The range of the energy production rate between the different approaches is relatively small, between 78 and 80%, suggesting that the use of stochastic optimization combined with ensemble forecasts leads to a significantly higher level of flood protection without compromising energy production.

Due to the fact that the São Francisco River catchment area has a vital role in the current Brazilian drought impact mitigation policy for the NE semi-arid part of the country and to the development an impoverished and underdeveloped region, a broader problem approach is required to evaluate the dynamic iterations between floods, droughts and society. Improvements in the current Water Disaster Management Policies are also required: development of more early-warning systems; development of resilience enhance measures; comprehensive disaster risk assessment policies; and improved mechanisms for vulnerability assessment and reduction.

Creating synergy between weather forecast techniques and better disaster reduction policies

Since the mid-1990s, the World Conference on Disaster Risk Reduction (WCDR) is held to promote discussions between governmental institutions and other stakeholders (NGOs, the private sector, civil society organizations and local governments) on disaster risk reduction and building disaster resilience.

At each WCDR new and improved disaster risk reduction guidelines and strategies are introduced. In 1994, at the first WCDR hosted in Yokohama, Japan, the Yokohama Strategy for a Safer World was adopted. During 2005 at the second WCDR conference held in Kobe, the Hyogo Framework for Action (2005–2015) was introduced; which would be replaced in 2015 at the third WCDR by the Sendai Framework for Disaster reduction (2015–2030).

The Yokohama Strategy identified that a more pro-active approach towards informing, motivating and involving people in all aspects of disaster risk reduction was needed and highlighted scarcity of resources for the realization of risk reduction objectives; whereas the Hyogo Framework is a detailed guideline for the coordination of different sectors and actors on disaster loss reduction (United Nations 2007, 2015*a*).

Water-related disaster risk management and integration of policies and coordination of stakeholders are also approached by the Agenda 2030 and its 17 Sustainable Development Goals (SDGs), introduced at the United Nations Rio + 20 summit in Brazil in 2012. The SDGs were integrated into the follow-up to the Millennium Development Goals (MDGs), established in 2000s, after their deadline in 2015 (United Nations 2015*b*). Griggs *et al.* (2013), suggested that these new goals should be more embracing than the MDGs, as they should not only focus on extreme poverty reduction in developing countries, but also on the transition to sustainable lifestyles in every nation around the globe.

This new framework also approaches Integrated Water Management and Water-Disasters mitigation as the goals 6, 7, 11 and 13, respectively: 'Ensure availability and sustainable management of water and sanitation for all'; 'Ensure access to affordable, reliable and modern energy for all'; 'Make cities and human settlements inclusive, safe resilient and sustainable'; and 'Take urgent action to combat climate change and its impacts'. They all have targets and indicators directly or indirectly related to water resources management implementation, water-related disasters risk reduction and resilience, mitigation and adaptation to climate change and early warning (United Nations 2015*b*).

Analysing the integration and effectiveness of the SDGs, both Le Blanc (2015) and Stafford-Smith *et al.* (2016) agreed that they were indeed broader and more integrated than their predecessors by linking social, economic and environmental aspects through a set of transversal goals. However, they also indicated that more integration across sectors in terms of strategies, policies and implementation is desirable. It was also emphasized that the success of the SDGs depends on a multi-stakeholder effort, involving different levels of national and local government, but also on collaboration of other organizations such as the private sector, philanthropic and international organizations.

In recent years cross-disciplinary integration with social resilience concepts have also been highlighted as an important step towards adaptive planning for climate change in vulnerable regions (Dale *et al.* 2015). Sivapalan (2015) presents an interesting paradigm to this wider problem through a coupled socio-hydrology-flood model which allows exploration of the resulting coevolution of floods and societies, with a focus on the estimation of emergent flood risk. In contrast to the current and traditional approach, where for a chosen design period, flood risk is estimated as a combination of flooding probability and its potential damages. This new approach permits analysis of the dynamic interactions and feedbacks between floods and societies, making better long-term strategic water management plans thereby avoiding long-term misunderstanding of the dynamics.

Table 3. *Brazil's expenditure on natural disasters' mitigation action (2014–2018)*

Year	Natural Disasters National Programme (BRL)	CEMADEN – Monitoring (BRL)	CEMADEN – Implementation (BRL)	Total (BRL)
2014	24 366 250.27	7 166 852,82	14 215 883,53	45 748 986.62
2015	14 962 942,06	6 965 929,76	7 466 568,99	29 395 440 81
2016	1 924 363.15	11 117 196.96	0.00	13 041 560.11
2017	598 464.01	8 852 297.25	0.00	9 450 761.26
2018	78 843.23	7 957 422.21	0.00	8 036 265.44
Total	41 930 862.72	42 059 699.00	21 682 452.52	105 673 014.24

Alongside structuration and structuring actions, natural protection has also positive impacts on flood mitigation. In a historical examination on the benefits and costs of Natural Valley Storage Protection, Kousky (2015) highlighted benefits of the economics and politics of 'green' flood control. The cost of large-scale land acquisition outweighed the sole benefits of avoided flood damage, indicating land use regulation as a cheaper alternative to land purchase.

However, due to political and economic factors the Agenda 2030 and Hyogo framework are at risk in Brazil. The official discussion about ways to implement and monitor the SDGs at National Government level started late in 2016 with the establishment of the SDG National Commission (Brasil 2016*a*). As of late 2018, the SDGs in Brazil are still not fully implemented, with ongoing discussions on the goals and the revision of indicators (Ipea 2018).

According to Brasil Ministério de Minas e Energia & Empresa de Pesquisa Energética (2015), the budget for natural disasters mitigation has decreased since 2014: expenditures within the national programme for natural disasters and with CEMADEN (monitoring and implementation) reduced from BRL45.75 million in 2014 to BRL8 million in 2018 (Table 3).

In addition, a Federal budget cut for next 20 years was passed in 2016, compelling further budget cuts to an area already lacking in financial resources: likely to jeopardise new improvements in the given governance and structure (Brasil 2016*b*; Mariano 2017; Vairão Junior & Alves 2017). These are also clear indications of a lack of governmental commitment not only to the current water risk reduction structure, but also the need for the integration of water risk reduction policies at all levels, which are likely to inhibit the success of mitigation action in the long term (Lassa *et al.* 2018).

Conclusions

Climate change is likely to enhance the uncertainty and magnitude of extreme weather events in Brazil, causing longer and more severe droughts, and higher peak flows in wet seasons. As these extreme phenomena become more frequent, impacts on important human activities such as agriculture, water supply and hydropower generation will have to be addressed on a regular basis.

As agriculture is one of Brazil's most important productive sectors, and one of the most vulnerable to weather disturbances, the consequences of an increased likelihood of extreme precipitations and longer dry spells may result in negative impacts to the country's economic growth, a rural exodus, an increase in regional differences and higher pressure on public services in urban centres. Therefore, better understanding of the local weather and hydrology is required, thus better weather forecasting and predictive models are essential tools to mitigate and reduce negative impacts of droughts and floods.

In all recent major extreme-weather events in Brazil the impacts on the local vulnerable population had severe impacts and losses especially on vulnerable populations, indicating governmental agencies' unpreparedness in efficiently undertaking disaster risk reduction and implementing adaptation strategies that cope with the negative impacts of these events. Thus, it is imperative to develop tools to help improve preparedness to extreme events, such as early-warning systems and high-resolution climate scenarios for impacts and adaptation studies.

The current drought and flood policies are not focused on vulnerability reduction but instead are centred on impact mitigation. Budget cuts and demobilization of institutions and agencies responsible for early-warning systems and disaster risk reduction hinder the vulnerability reduction required to understand and practise climate-change adaptation.

Advancements in climate and hydrology monitoring and the improvement of regional and local weather forecast models can have a vital role in extreme weather adaptation and resilience, as they serve as tools for policymakers in implementing adaptation strategies to cope with climatic hazards. The further development and dissemination of these technique have the potential to improve the Integrated Water Resources Management at all levels of users.

It is important to stress that for the full success of the techniques and policies currently being applied to assess how droughts and floods impacts the health and livelihoods of people living in these regions, it is imperative to implement other measures that would greatly improve the flood control and water-disasters resilience. These include well-suited government policies aimed for adaptation and vulnerability assessments for the population. The Agenda 2030 should be used as catalyst for this change, integrating policies, strategies and sectors with social, economic and environmental goals.

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