esd-2016-65
Drought and Flood in the Anthropocene: Modelling Feedback Mechanisms
Giuliano Di Baldassarre, Fabian Martinez, Zahra Kalantari, and Alberto Viglione

RESPONSE LETTER

We would like to thankfully acknowledge the Editor, Prof. Sivapalan, and the two Anonymous Referees for providing constructive comments about our paper. All comments were carefully considered, and we believe they helped us improve the description of our work.
We provide here a **point-by-point response**, and specify the way we addressed all comments.
A **marked-up manuscript version** is reported at the end of this Response Letter.

RESPONSE TO Reviewer#1

The paper by Di Baldassarre et al purports to present a stylized model of hydrological extremes and human responses. This is an exciting and important research area. However, this general framing is overly broad for the analysis performed. The actual model presented illustrates interactions between drought and flood events and human operation of reservoirs. Thus, the motivation and introduction of the paper should be more closely aligned to the model presented. Also, the model and analysis feel a bit "thin". A singular case study of "drought-thenflood" is presented for Brisbane. The authors need to show that their stylized model can capture other drought-then-flood time series, AND, importantly, that it is also able to replicate "floodthen-drought" events, as both are major motivations of the study. I suggest some major revisions that the authors may choose to undertake to make the paper more suitable for publication

We would like to thank the Referee for providing constructive comments about our paper, which we believe will help us improve the description of our work.

One issue highlighted by the Referee is that the paper is too broad in the introduction and motivation while too narrow in the modelling exercise. This is partly due to the goal of the paper, which aims to propose a general research agenda on modelling floods and droughts in the Anthropocene, and then describe a first initial attempt in that direction.

Yet, the Referee has a point and her/his comment clearly shows that there is a discrepancy between the two parts of the paper. The paper was revised following the suggestion of the Referee. In particular, we:
i) changed the title of the paper to make it more specific (with a clear reference to "feedback mechanisms in reservoir operation" see also Response to Reviewer #2),
ii) made a more focused introduction, which also specifies better the aim (see revised Introduction), and goal of this simple model.
iii) expanding the modelling exercise and including a flood-then-drought simulation (see new figures 5b, 6a, and 6b).

MAJOR COMMENTS

1. In many places, the authors claim to examine “human impacts”, “human interactions”, and “water management”. However, the authors solely consider dam operations. The paper should be re-written to bring the motivation more in line with the actual model presented.

As stated above, we change the title and revised the introduction to increase focus on reservoir operations. Previous references to risk (lines 10-15 in the original manuscript) and other human impacts, such as water abstraction, irrigation and levees (lines 20-25 in the original manuscript) were removed.

2. The analysis is a bit “thin”. a. Fig 5 presents the main piece of analysis in the paper, which is for a droughtthen-flood occurrence in Brisbane. What are the specific parameters used? How sensitive are the results to various parameter combinations? A sensitivity analysis is necessary. b. What about other discharge time series? The study seek to understand if and how “human responses to drought events might exacerbate the impact of future floods, and vice versa” (Page 5, Lines 20- 25). Yet the only case study presented explores one occurrence of a droughtthen-flood in Brisbane. Can the model fit other similar occurrences of drought-then-flood? Are the model parameters the same? Importantly, can the model fit occurrences of flood-then-drought? What happens to the model parameters in this temporal sequence of hydrological extremes?

It is a very good point. We included an additional experiment to show a scenario of flood-then-drought as suggested by the Referee (see new Figure 6). We also included details about parameterization and initial conditions (see revised Tables 1 and 2). Also, we included new diagrams to show how the storage coefficient changes over time as a result of flood and drought memories change (see new Figure 5b and 6b).
As mentioned, we also clarified the goals of this paper of proposing a general research agenda on modelling floods and droughts in the Anthropocene, and then describing a first initial attempt in that direction (see revised Introduction in word track change). We do acknowledge that more research is needed to test more models as competing hypotheses on other case studies and via a broad sensitivity analysis.

3. The generic term “hydrological risk” is used, which is “broadly defined as a combination of hazard, vulnerability, and exposure”. The natural hazard community has been trying very hard to be precise in terminology to avoid confusion and keep the external, physical driver distinct to the internal, societal vulnerability. Please be precise with terminology throughout your paper to avoid confusion.

According to our experience the number of definitions of risk, and each component of risk, is immense. Even within the natural hazards community.
Note that the suggested dichotomy made above between internal/societal and external/physical driver would in fact be not coherent with the methodological approach proposed here, which emphasises the two-way human-water interactions.
In other words, the external drivers of risk are for both on the physical and societal sides, likewise the internal drivers of risk are for both on the physical and societal sides (Figure 3).
Anyhow, a critical reflection on the nature of risk is out of the scope of this work. Thus, we left risk broadly defined as a combination of hazard, vulnerability and exposure, which is in

fact a widely used the definition of risk (e.g. IPCC, 2014). This reference to IPCC has been added to the revised manuscript.

MINOR COMMENTS

1. Throughout, terminology should be clarified to make the reader more able to understand if "reservoir inflow", "storage", or "reservoir outflow" are being considered. For example, "natural river flow" in Fig 1 is confusing and would be more clear as "reservoir inflow". Generally, it should be readily apparent if flows upstream or downstream of the reservoir are being referred to.

We thank again the Referee for spotting the use of inconsistent terminology, suggesting additional discussion on a number of interesting points, and raising technical issues with figures and captions. We revised the paper accordingly.

2,3,4 Page 9, Line 14. "Actual river flows" à "reservoir outflows" 3. Caption of Fig 1. Higher flows during drought conditions? This doesn't make sense. Please clarify. 4. Label equation variables on Fig 1. "Inflow" should be Q_N and "outflow" should be Q

The revised paper will refer to inflow, outflow, and storage consistently. A specific paragraph will then be added to clarify cases in which inflow can be considered as representative of natural conditions while outflow can be considered as representative of actual (human-modified) conditions.

5. Page 5, Lines 20-25. Interesting! Can you expand upon your Melbourne time series and show more combinations of this?

We also added reference to the ongoing Oroville Dam crisis in California, which is one of the most recent disasters generated by high flow conditions that occurs immediately after prolonged droughts.

6. Figure 2. Please label panels as A and B. For the right panel, do you show population time series of only flood-prone areas of Rome? Is population growth in flood-prone areas of Rome distinct to population growth in all of Rome? Importantly, is population growth shown here different to global urban population growth? Are you really just plotting the global urbanization trend?

Panel were labelled A and B. It is not about global urbanisation trends: without levees all these floodplain districts in Rome could not be built as flooding would have be too frequent and made these places inhabitable. The case of Rome and the urbanization trends are in fact quite complex. This is now better explained in a recently published paper about human-flood interactions in Rome (Di Baldassarre et al., 2017). The manuscript now clarifies this point and refer to this most recent study.

7. Figure 4. Why do you plot policies per capita? Are you really just plotting the population growth rate in inverse here?

7. Data are given as policies per capita by Hanak et al. (2011), but the figure does not plot the population growth rate in inverse. For instance, the diagram shows that in 6 years (from 1998 to 2004) policies per capita halved (from 1,5% to about 0,75%) and California's population did not double in 6 years. Yet, we clarified this in the revised manuscript by explicitly stating (in the figure's caption) that in the same period policies per capita in the entire USA were essentially stable (Hanak et al., 2011).

8. Figure 5. Please use different symbols for "coping with flood" and "coping with drought" lines, for those of us that do not print in color.

Amended. This works in black and white now.

9. Table 1 and 2. Combine into a single table. Present tables with parameters used for all case studies presented (should be more than one case study in the revised version of the paper).

We added the initial conditions for the time-varying variables (Table 1) and the values of the time-invariant parameters used in the simulation (Table 2). Yet, we did not combine the two tables to keep a clear differentiation between time-varying variables and time-invariant parameters.

10 Conclusion outlines some data sources. The mismatch in spatial and temporal scale between physical and human data should be briefly mentioned and discussed.

10. Good point. A paragraph was added at the end of the conclusions to discuss the mismatch in spatial and temporal scale between hydrological and social data, as well as the need to deal with both quantitative and qualitative data. Reference to Driscoll et al. (2007) was also added for this purpose.

11. The current goal of coupled human-natural (CNH) modeling is to capture feedbacks between human-natural systems, as well as internal feedbacks in human systems and internal feedbacks in natural systems. You should make it clear in your schematic (Fig 3) that you only focus on feedbacks between human-natural systems.

11. The focus on the internal feedbacks between water and human system was underlined in the caption of Figure 3.

ADDITIONAL REFERENCES

Di Baldassarre, G., Saccà, S., Aronica, G. T., Grimaldi, S., Ciullo, A., and Crisci, M.: Human-flood interactions in Rome over the past 150 years, Adv. Geosci., 44, 9-13, doi:10.5194/adgeo-44-9-2017, 2017.

Driscoll, D.L., A. Appiah-Yeboah, P. Salib, and Rupert D.J.: Merging qualitative and quantitative data in mixed methods research: how to and why not. Ecological and Environmental Anthropology, 3(1), 2007.

RESPONSE TO Reviewer#2

This manuscript presents a framework for analyzing the feedback mechanisms of human activities and floods and droughts. The main focus is on reservoir operation and the corresponding feedbacks during droughts and floods. The framework is based on a so-called virtual model that can be used to understand the broad feedbacks between the two system (and not necessarily based on site specific rules of operation schemes). The notion of flood and drought memory, used here in the model, is really interesting and has not explored much in the past. Overall, I believe this is a good contribution and should be considered for publication after addressing the below.

We would like to thank the Referee for providing constructive comments about our paper, which we believe will help us improve the description of our work. We provide here a first response to all comments and indicate the way we aim to address them during the review process.

The manuscript presents an example of modelling flood and drought (Figure 5) including the actual river flows, and result from changing norms in reservoir management between operation rules aiming to better cope with flood, and operation rules aiming to better cope with drought. It would be great if the authors can plot a similar graph based on reservoir storage (i.e., observed storage, storage when the system is optimized to cope with drought, and storage when the system is optimized to cope with floods). Ideally, storage should be presented in percent of the total.

We welcome the Referee's suggestion to complement figure 5. We did not include reservoir storage though as it is linearly related to the outflow (equation 2) so there is no much information from it. We included instead the storage coefficient over time (actual one, optimized to cope with drought, and optimized to cope with floods). See new Figure 5 and 6.

The model structure is explained well. But the parameter estimation component needs more explanation. I understand the the storage coefficient is estimated as a weighted average between a value that allows to have enough volume available during major flood events (kf), and a different value that enables to keep enough water in the reservoir to cope with drought conditions (kd). Please explain how kf and kd are estimated. There are other parameters in Equations 4 to 6. Are they assumed or estimated using a parameter estimation scheme?

We agree with the Referee that parameter estimation needs more explanation. Given the virtual nature of this numerical experiment all parameters are assumed. This aspect is now clarified in the revised manuscript and the parameter values are now reported in Table 2. Also, Table 1 shows the initial conditions for the variables.

The model uses a dynamically changing storage coefficient (k) to explain the changing rules for reservoir operation. Please explain the time scale of variability. Does this parameter change at monthly scale? Or seasonal?

The time scale of variability is annual in the example provided in Figure 5, but can in principle also be monthly or seasonal (though this would include more complex reservoir operation rules). This is now explained in the text.

It would be good to report the estimated parameters in Appendix or Supplementary

We added them in Tables 1 and 2.

Given that the model is designed to simulate long-term changes, shouldn't there be a loss term to account for direct evaporation from reservoirs? Evaporation is higher when the goal is to store water over a much longer period than when it is released faster. This may not be a big factor in overall balance. But just something to think about.

The Referee makes a good point about evaporation. The model does not account for it for the sake of simplicity, but this aspect is now explicitly mentioned in the revised manuscript in describing model limitations (see below).

During droughts, typically, the demand is managed downstream which means the releases from reservoirs will change (i.e., a two-way feedback between demand and storage). If I understand correctly, this model does not consider this issue (?). It is worth including a brief discussion on this issue.

This feedback between water demand and storage is not explicitly considered here (see also next point), but if we understand the Referee's point correctly this aspect is at least partially (implicitly) captured by the changing storage coefficient that tends to increase during drought condition and therefore reduce outflow.

I suggest adding a paragraph or two on the general limitations of the model including the underlying assumptions (e.g., linearity).

We agree with the Referee and therefore added a paragraph illustrating the limitations of the model stating that "as we focus on the feedback mechanisms between flood or drought occurrence and changing reservoir operation rules, this model is highly simplified and does not account for other aspects, including the direct evaporation from the reservoir, the control of overflows (e.g. spillways), and the feedbacks between water supply and demand".

The focus of the model is on human impact on water storage in reservoirs. I suggest making this clear in Abstract. The current version is too broad and implies a much broader human impact assessment. Also, I suggest considering adding something like C3 ESDD Interactive comment Printer-friendly version Discussion paper this to the title "Feedback Mechanisms in Reservoir Operation".

Indeed, as discussed in our Response to Referee#1, we clarified the focus of the paper and the model in the Abstract as the original version was too broad. Also, we changed the second part of the title as suggested, i.e. "Feedback Mechanisms in Reservoir Operation".

Drought and Flood in the Anthropocene: Feedback Mechanisms in Reservoir Operation ~~Modelling Feedback Mechanisms~~

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Abstract. Over the last few decades, numerous studies have investigated human impacts on drought and flood events, while conversely other studies have explored human responses to hydrological extremes. Yet, there is still little understanding about the dynamics resulting from their interplay, i.e. both impacts and responses. Current quantitative methods therefore can fail to assess future risk dynamics and, as a result, while risk reduction strategies built on these methods often work in the short term, they ~~can~~ tend to lead to unintended consequences in the long~~er~~ term. In this paper, we review the puzzles and dynamics resulting from the interplay of society and hydrological extremes, and describe ~~our~~ an initial effort~~s~~ to model hydrological extremes in the Anthropocene. In particular, we first discuss the need for a novel approach to explicitly account for human interactions with both drought and flood events, and then present a stylized model simulating the reciprocal effects between hydrological extremes and ~~water management~~changing reservoir operation rules. ~~, drought and flood events.~~ Lastly, we highlight the unprecedented opportunity offered by the current proliferation of big data to unravel the coevolution of hydrological extremes and society across scales, and along gradients of social and hydrological conditions.

1 Introduction

Throughout history, human societies have been severely impacted by hydrological extremes, i.e. drought and flood events. The collapse of various ancient civilizations, for instance, has been attributed to the occurrence of hydrological extremes (e.g. Munoz et al., 2015). Fatalities and economic losses caused by drought and flood events have dramatically increased in many regions of the world over the past decades (Di Baldassarre et al., 2010; Winsemius et al., 2015) and, currently, more than 100 million people per year are affected by hydrological extremes (UN-ISDR, 2016). There is serious concern about future hydrological risk (broadly defined here as a combination of hazard, vulnerability and exposure, e.g. IPCC, 2014) given the potentially negative impact of climatic and socio-economic changes (Hallegatte et al., 2013; Jongman et al., 2014~~; IPCC, 2014~~). Thus, it is essential to realistically capture where, how and why risk will plausibly change in the coming decades, and develop appropriate policies to reduce the negative impacts of hydrological extremes, e.g. economic losses and fatalities, while retaining the benefits of hydrological variability, e.g. supporting biodiversity and ecosystem functions.

Human societies have (intentionally or accidentally) altered the frequency, magnitude and spatial distribution of flood and drought events (Falkenmark and Rockström, 2008; Di Baldassarre et al., 2009; Vörösmarty et al., 2013; Blöschl et al., 2013; Montanari et al., 2013; AghaKouchak et al., 2015; Destouni et al., 2015; Van Loon et al., 2016). Dams and reservoirs are examples of water management measures that deliberately change hydrological variability (Ye et al., 2003) and significantly affect hydrological extremes, as schematically depicted in Figure 1.

~~Moreover, water abstraction and irrigation have a significant impact on the occurrence of hydrological drought (Van Loon et al., 2016); while flood protection measures, such as levees, alter the frequency, magnitude and spatial distribution of flood events (Di Baldassarre et al., 2009; Blöschl et al., 2013; Heine and Pinter, 2012). Hydrological extremes can also be affected by other human activities such as land-use change, deforestation, urbanisation, drainage of wetlands and agricultural practices (Kalantari et al., 2014; Savenije et al., 2014; Destouni et al., 2015).~~

While human societies shape hydrological extremes, hydrological extremes in turn shape human societies. Following the impact of drought or flood events, humans respond and adapt to hydrological extremes through a combination of spontaneous processes and deliberate strategies that can lead to changes in social contracts (Adger et al., 2013). Adaptive responses can take place at the individual, community or institutional level (Myers et al., 2008; Penning-Rowsell et al., 2013). Early warning systems, risk awareness programs, and changes of land-use planning are examples of adaptive responses that often occur at the local or central government level following hydrological extremes (Pahl-Wostl et al., 2013). Moreover, structural risk reduction measures, such as reservoirs or levees, are also planned, implemented or revised after the occurrence of drought or flood events, and they in turn (again) change the frequency, magnitude and spatial distribution of hydrological extremes (Di Baldassarre et al., 2013a).

In the recent decades, natural and engineering scientists have analysed numerous facets of human impacts on drought and flood events, while conversely economists and social scientists have explored human responses to hydrological extremes. Yet, the dynamics resulting from the mutual shaping (i.e. both impacts and responses) of hydrological extremes and societies are still not well understood. As a result, current quantitative methods fail to assess the dynamics of hydrological risk and, while risk reduction strategies built on these methods often work in the short term, they can lead to unintended consequences in the long term. To overcome this lack of knowledge, there has been increasing interest in socio-hydrology in the last few years (e.g. Sivapalan et al., 2012; Srinivasan et al., 2012; Di Baldassarre et al., 2013b; Montanari et al., 2013; Schumann and Nijssen, 2014; Viglione et al., 2014; Elshafey et al., 2014; van Emmerick et al., 2014; Sivapalan and Bloeschl, 2015, Loucks, 2015; Troy et al., 2015; Gober and Weather, 2015; Pande and Savenije, 2016; Blair and Buytaert, 2016), which aims to develop fundamental science underpinning integrated water resources management (IWRM). Socio-hydrology builds on a long tradition of studies exploring the interplay of nature and society and the implications for sustainability, including political ecology, social-ecological systems, ecologic economics, complex system theories and research on planetary boundaries (Swyngedouw, 1999; Folke et al., 2005; Liu et al., 2007; Ostrom, 2009; Rockström et al., 2009; Kallis and Norgaard, 2010).

In this context, this paper ~~describes~~ summarises the puzzles and dynamics emerging from the interplay of society and hydrological extremes, discusses the need for a novel approach to explicitly account for both drought and flood events, and ~~presents~~ describe an initial effort~~s~~ to model hydrological extremes in the Anthropocene by means of a stylised model of feedback mechanisms in reservoir operation.

2 Emerging dynamics and puzzles

Various dynamics result from the interactions between human societies and hydrological extremes. Learning or adaptation effects emerge when more frequent events are associated with decreasing vulnerability (Di Baldassarre et al., 2015). This effect can be attributed to informal adaptive processes, such as temporary and permanent migration, or changes in policies triggered by the occurrence of hydrological extremes (Pahl-Wostl et al., 2013). For instance, Mechler and Bouwer (2014) showed decreasing flood fatalities in Bangladesh over the past 40 years (Figure 2~~, left panel~~A). This reduced vulnerability can be attributed to coping and adaptation capacities gained by individuals or communities after the experience of extreme events. Moreover, Di Baldassarre et al. (2017) showed how the construction of levees protecting flood-prone areas in Rome have facilitated increasing floodplain population in Rome, Italy (Figure 2B).

Societies are not only shaped by the occurrence of hydrological extremes, but also by the perception of current and future risk (Dessai and Sims, 2010). This can explain the emergence of what is termed here as the forgetting or levee effect, i.e. less frequent events associated with increasing vulnerability. Since White (1945), the literature has provided various examples that show that the negative impact of an extreme event tends to be greater if such an event occurs after a long period of calm. Prolonged absence of drought or flood events can be caused by climatic factors (e.g. flood-poor periods; Hall et al., 2014) or the introduction of structural risk reduction measures, such as reservoirs (Figure 1). One example is the case of Brisbane, where the introduction of a flood retention reservoir in the 1970s has shaped risk perception in the local community, which perceived Brisbane as flood-proof until a catastrophic flood event occurred in 2011 (Bohensky and Leitch, 2014).

Learning and forgetting effects have been reported in different parts of the world in a variety of empirical studies, e.g. collection of case studies reported in Di Baldassarre et al. (2015). The emergence of these dynamics suggests the intuitive tendency that the impact of drought or flood events depend on whether their occurrence is expected or not. Yet, these dynamics have mainly been reported as narratives in specific case studies. It is still unclear whether they are exceptional cases or generic mechanisms, and whether they occur randomly or within certain social and hydrological circumstances. This lack of knowledge prevents their explicit inclusion on the analytical tools that undertake a quantitative assessment of hydrological risk.

Besides the inability to capture learning and forgetting dynamics, traditional methods for risk assessment cannot explain interactions between floods, droughts and water management as they focus on either drought or flood hazard (e.g. Shahid and Behrawan, 2008; Jongman et al., 2014). For instance, while reservoirs theoretically alleviate both flood and drought events (Figure 1), reservoir operation rules (Mateo et al., 2014) mitigating drought are different from the ones mitigating flood. To cope with drought, reservoirs are typically kept as full as possible, working as a buffer during low flow conditions, whereas to cope with flood, reservoirs are often kept as empty as possible, allowing the storage of a large quantity of water from extreme rainfall or rapid snow melt conditions. These reservoir operation rules can change over time depending on various factors, including whether the most recently experienced disaster was caused by a drought or a flood event. As a result, the negative impact of flood events occurring immediately after a long period of drought conditions can be exacerbated.

For example, the aforementioned catastrophic 2011 flooding of Brisbane occurred after an exceptionally long, multi-year drought (the so-called “Millennium Drought”; Van Dijk et al., 2013), which triggered changes in reservoir management (van den Honert and John McAneney, 2013). In particular, operation rules of the flood mitigation reservoir build in 1970s were changed, and the reservoir was used instead as a buffer to cope with drought conditions. This change in operation rules led to higher water levels in the reservoir, which was then less unable to store much water and alleviate the 2011 flood event. Meanwhile, paradoxically, the presence of the reservoir triggered the popular belief that Brisbane was flood proof and made the population more vulnerable. The combination of these events made the 2011 flooding a major disaster (Bohensky and Leitch, 2014).

Research on climate change suggests that many regions around the world might experience, in the near future, alternate periods with prolonged drought conditions and extreme flood events (IPCC, 2014). The 2017 Oroville Dam crisis in California is one of the most recent disasters generated by high flow conditions that occurs immediately after prolonged droughts. Thus, it is vital to understand if (and how) human responses to drought ~~events~~ might exacerbate the impact of future floods, and vice versa.

Furthermore, a focus on either drought or flood events can limit the interpretation of the role of global drivers of hydrological risk, such as climatic and socio-economic changes. For example, a number of recent studies (e.g. Di Baldassarre et al., 2010; Winsemius et al., 2015) have shown that socio-economic changes have been the main driver of increasing flood risk in Africa, while climate has (so far) played a smaller role. Yet, by focusing on flood risk alone, these studies did not consider the hypothesis that climate may have led to longer and more severe drought conditions, which in turn have enhanced the need for individuals and communities to move closer to rivers, thus leading to greater exposure to flooding.

Thus, it is still largely unexplored how sequences of drought and flood events make a difference in the dynamics of hydrological risk. This puzzle requires further research on the mutual shaping of human societies and hydrological extremes, to which this paper aims to contribute.

3 Hydrological extremes in the Anthropocene

To reveal the aforementioned dynamics resulting from the mutual shaping of hydrological extremes and society, there is a need for both empirical and theoretical research exploring numerous river basins, floodplains and cities as coupled human-water systems. Figure 3 schematizes how internal feedback mechanisms within the systems consist of: i) impacts and perceptions of hydrological extremes that shape society in terms of demography, institution and governance, and ii) policies and measures implemented by society that shape hydrological extremes in terms of frequency, magnitude and spatial distribution. These internal dynamics also interact with external drivers of change operating on larger or global scales (Figure 3), i.e. climatic and human influences outside the system (Turner et al., 2003).

One of the challenges in unravelling the interplay of hydrological extremes and society is the different time and space scales of drought and flood events. While the duration of flood events ranges from hours to days, drought has much longer lifetimes, in the order of weeks, months or even years. Similarly, spatial scales of flood events are typically smaller than those of drought conditions (Van Loon, 2015). As a result, the integrated effects of these hydrological extremes on society and the associated feedback loops are significantly different. For instance, at level of crisis management, more time for decision making is available in the case of drought than for flood events. Also, while some flood protection measures can decided and implemented at the local level within one or few municipalities, drought policies require agreements at regional scales.

Yet, water management policies account for both hydrological extremes. Moreover, for large river basins, the periodicity or clustering of drought and flood events seem to be more coherent in time and space. This due to mass balance reasons as well as the fact that flood and drought periods are often produced by atmospheric blocking (e.g. Francis and Vavrus, 2012). Lastly, as mentioned in the previous section, the dynamics of human impacts on flood events depend on human responses to drought events, and vice versa. Thus, in the Anthropocene, it is essential to consider both hydrological extremes.

In this context, we present a new model that mimic the interplay between water management and hydrological extremes. This conceptualisation builds on similar efforts that were recently made in socio-hydrology (Di Baldassarre et al., 2013b; 2015; Viglione et al., 2014; Kuil et al., 2016), which modelled either drought or flood events, but not both hydrological extremes. Our model focuses on the human impact on water storage via reservoirs. As the model aims to explore emerging patterns resulting from generic mechanisms, it was not based on site specific rules of operation or optimization methods. Instead, the model was inspired by the criticism of rational decision making and optimization made by numerous scholars following the work of the Nobel laureate Daniel Kahneman. In particular, Tversky and Kahneman (1973) formulated the availability heuristic as the bias due to the fact that decision makers estimate the probability of events not only based on robust evidence, but also “by the ease with which relevant instances come to mind”. Tversky and Kahneman (1973) showed that this judgmental heuristic leads to systematic biases. By extending this concept, we develop a stylised model that simulate the mutual shaping of hydrological extremes and water management.

The model is based on the use of a reservoir, which is used to schematically characterise changes in water storage caused by human activities (Figure 1). ~~, ~~In particular, by considering a time series of natural river discharge (Q_N) as natural inflow, the ~~actual river discharge~~human-modified outflow (Q) can be derived ~~as outflow ~~from the variation in time of the reservoir storage (S) using a mass balance equation:

$$Q = Q_N - \frac{dS}{dt} \tag{1}$$

By assuming a linear reservoir with a storage coefficient (k), the human-modified outflow ~~actual river discharge ~~is related to the ~~volume of water stored in the ~~reservoir storage ~~(S) as~~by:

$$Q = \frac{S}{k} \tag{2}$$

To capture the typically high release of water when reservoirs are full, e.g. overflows, we assume that if the storage ~~(*S*)~~ is above a certain threshold (*S*$_{max}$), the ~~actual river discharge~~human-modified outflow will have an additional component which is, for the sake of simplicity, linearly proportional to the difference between *S* and *S*$_{max}$ with an overflow coefficient (α):

$$Q = \frac{S}{k} + \frac{(S - S_{max})}{\alpha} \tag{3}$$

We then use a dynamically changing storage coefficient (*k*) to explain the changing rules for reservoir operation. This storage coefficient is estimated as a weighted average between a value that allows to have enough volume available during major flood events (*k*$_f$), and a different value that enables to keep enough water in the reservoir ~~to~~ and better cope with drought conditions (*k*$_d$):

$$k = \frac{M_f \cdot k_f + M_d \cdot k_d}{M_f + M_d} \tag{4}$$

Equation (4) shows that the weights are given by two contrasting memories of the reservoir management system, i.e. flood memory (*M*$_f$) and drought memory (*M*$_d$), which are assumed to change over time depending of actual flow conditions:

$$\frac{dM_f}{dt} = \mu\left(\frac{Q^\beta}{Q_{N,mean}^\beta} - M_f\right) \tag{5}$$

$$\frac{dM_d}{dt} = \mu\left(\frac{Q_{N,mean}^\beta}{Q^\beta} - M_d\right) \tag{6}$$

Equations (5) and (6) formalize our assumption that flood memory is accumulated more than drought memory during high flow conditions ($Q > Q_{N,mean}$), while drought memory is accumulated more than flood memory during low flow conditions ($Q < Q_{N,mean}$). This assumption is inspired by the aforementioned availability heuristic (Tversky and Kahneman, 1973) and based on the empirical evidence that preparedness ~~is~~ tends to be ~~very~~ higher immediately after the occurrence of extreme events, which ~~that~~ often lead to additional pressure for changes in water management. For example, Hanak (2011) reports the decline in flood insurance coverage in California after the 1997 Central Valley flooding (Figure 4).

Equations (5) and (6) also describe that both drought and flood memories diminish exponentially over time with a decay rate μ. This assumption is based on previous models of human-flood interactions (Di Baldassarre et al., 2013b; 2015; Viglione et al., 2014; Grames et al., 2016), as well as scientific work on individual and collective memory (Anastasio et al., 2012).

The exponent β in equations (3) and (4) is used to characterize the level of bias caused by the difference between drought and flood memories. In particular, for $\beta = 0$ both memories tend to the value of 1 over time, and k becomes constant. This can be used to describe a rational decision making system whereby the proportion between k_d and k_f is derived with an optimal design of the reservoir to balance relative weights of drought and flood events. Increasing β, indicates increasing bias as more dynamic variations of M_d and M_f occur during periods of high or low flow conditions, and consequently faster changes in reservoir operation rules. As a summary, Tables 1 and 2 report the state variables and time invariant parameters, respectively, of the stylised model presented here. It is important to note that, as we focus on the feedback mechanisms between flood or drought occurrence and changing reservoir operation rules, this model is highly simplified and does not account for other aspects, including the direct evaporation from the reservoir, the control of overflows (e.g. spillways), and the feedbacks between water supply and demand.

To show an example of the dynamics captured by this model, we compare the results obtained with variable reservoir operation rules, which depend on the changing drought and flood memories, with the results obtained by using fixed storage coefficient to cope with either drought or flood events (Figure 5). This virtual experiment is run by solving the differential equations numerically with a finite difference method, and using flow data of the river Brisbane as input, i.e. times series of natural ~~river discharge~~inflow (Q_N). Given the hypothetical nature of this simulation, parameters and initial conditions are assumed and reported in Tables 1 and 2.

Figure 5A shows the human-modified outflow resulting from changes in operation rules. ~~Figure 5 shows the s~~Shifts in ~~of~~ reservoir management are depicted in Figure 5B in terms of ~~-~~changing values of the storage coefficient using an annual time scale of variability.

~~and~~ while~~how actual river flows result from changes in operation rules~~. ~~In particular,~~

Figure 5A shows that the 2011 flood event would have had a much lower discharge if the reservoir operations aimed to cope with flood. Yet, ~~but~~ prolonged low flow conditions in the previous decade (i.e. Millennium drought) led to change in reservoir operations ~~that enable~~ to better cope with drought, i.e. keep more water in the reservoir instead. This change increased the reservoir storage and led to substancial ~~, which lead to~~ overflow and therefore an ~~enhance~~enhancement of 2011 ~~ed~~ flood outflows ~~levels~~. ~~A plausible~~This can be seen as a plausible interpretation of the remarkable severity of the 2011 Brisbane flood disaster~~ing~~.

To complement the above experiment of a flood event occurring shortly after a prolonged drought, we also use the model to explore the impact of a prolonged drought occurring shortly after a flood event. To this end, we make a virtual experiment by assuming the occurrence of exceptionally high flows just before the Millennium drought (Figure 6A). The occurrence of this major flood changes operation rules as depicted by Figure 6B, which shows the changing values of the storage coefficient. This shift made drought conditions more severe, i.e. during the Millennium drought the human-modified outflows are lower than the outflows of the “coping with drought” scenario (Figure 6).

4 Conclusions and perspectives

This paper described an initial attempt to study the coevolution of water management and hydrological extremes. This is considered a first step in a broad research agenda that includes both empirical and theoretical work to uncover the mutual shaping of hydrological extremes and society (Figure 3). In particular, as described by McDonald (1989) and then discussed by Di Baldassarre et al. (2016), the development of new knowledge typically require research efforts that can be classified into five main steps: 1. Data collection and analysis; 2. Examination of these data to determine salient facts that still need a formal explanation; 3. Theory development via formulation of models capturing the salient facts; 4. Model calibration, validation and uncertainty analysis; and 5. Application of models to support the decision making process. As discussed by McDonald (1989), some scientists are deeply “engaged in work that refines or makes use of the generally accepted model” (steps 4 and 5), while others are “in the process of questioning the generally accepted model” (steps 1-3). To better understand drought and flood events in the Anthropocene, we believe that research efforts should focus on steps 1-3, since coevolutionary dynamics are still largely unknown. In particular, to develop socio-hydrological theory, there is a need for iterations between historical analyses of case studies and formal explanations of the salient facts via stylized models, such as the one presented in this paper.

Besides case studies and dynamic models, an unprecedented opportunity to explore coevolutionary dynamics across spatio-temporal scales and socio-hydrological gradients is offered nowadays by the recent proliferation in global remote sensing data and worldwide archives at relatively high spatial (between 100m and 5km) and temporal (between one day and one year) resolution. In particular, by referring to the feedback loop in Figure 3, useful sources of data include: *Hydrological extremes*: outcomes of global hydrological models; worldwide river flow archives (Hannah et al., 2011); drought and flood inundation maps derived from satellite imagery (Di Baldassarre et al., 2011); *Impacts and perceptions*: global database of damage caused by droughts and floods (EM-DAT); social media such as Twitter and Facebook; *Society*: global population data and maps of human settlements (Linard et al., 2012); satellite nightlights as proxies for economic growth and human population density (Ceola et al., 2014); *Policies and measures*: global maps of land-use, irrigation, dams and reservoirs (Bierkens, 2015); information about flood protection standards in different countries (Scussolini et al., 2016). two main challenges are associated with the overlay of these different sources of big data: i) the mismatch in spatial and temporal scales of hydrological and social data, and ii) the need to integrate quantitative data with more qualitative information, e.g risk perception from Twitter data. This will require the development of new techniques and mixed research methods (Driscoll et al., 2007), allowing a global analysis of these data to reveal ~~Global comparative analyses can capitalize on this flood of data and explore~~ whether the emerging dynamics and puzzles described ~~in this paper~~here are either site-specific cases that occur randomly or general patterns that emerge under specific social and hydrological conditions.

Acknowledgements. The present work was developed within the framework of the Panta Rhei Research Initiative of the International Association of Hydrological Sciences (IAHS), within the working groups on “Changes in Flood Risk” and “Drought in the Anthropocene”. Brisbane river data were downloaded from the Water Monitoring Information Portal of Queensland Government, Department of Natural Resources and Mines (DNRM).

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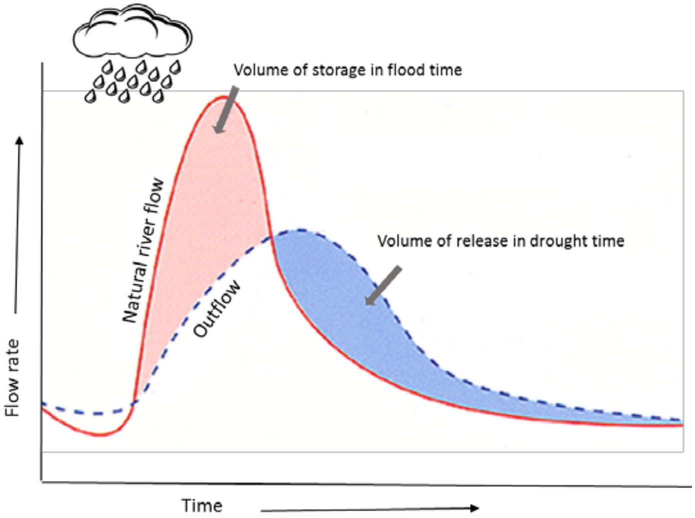

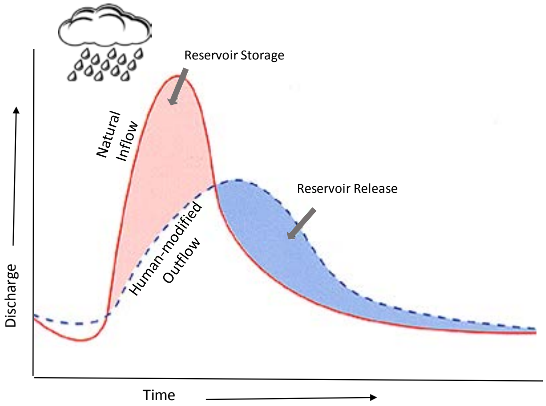

Figure 1: Human impact on hydrological extremes. Schematic example of the impact of dams and reservoirs, which tend to mitigate both hydrological extremes, i.e. lower outflows (blue dashed line) during high inflow (red line) conditions, ~~flood events and~~ higher outflow~~s~~ during low inflow ~~drought~~ conditions.

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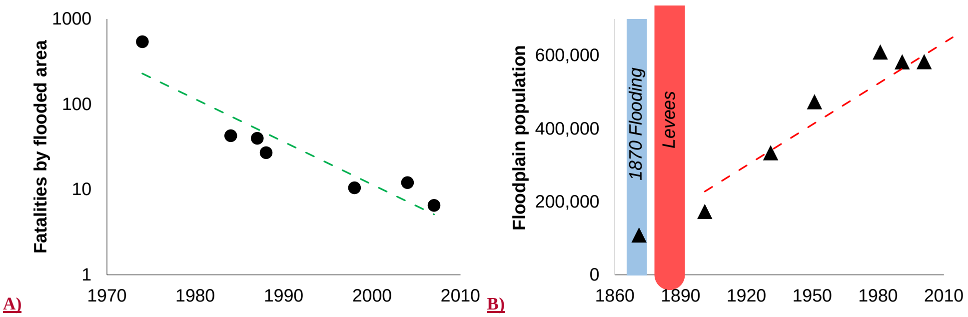


Figure 2. Examples of ~~L~~learning and forgetting effects. ~~The left panel shows~~A) decreasing flood fatalities normalized by flooded area in Bangladesh (data from Mechler and Bouwer, 2014). B) ~~, while the right panel shows~~ increasing population in flood-prone areas in Rome (Italy), following a prolonged absence of flooding due to the construction of levees (data from Ciullo et al., 2016).

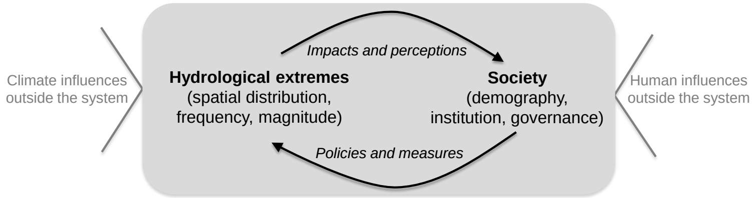


Figure 3: Hydrological extremes in the Anthropocene. Internal feedbacks within the human-water system (grey area, focus of this paper) at the local scale, ~~(in black)~~ and external drivers of change that operate at larger/global scale such as climate change and socio-economic trends. ~~(in grey)~~.

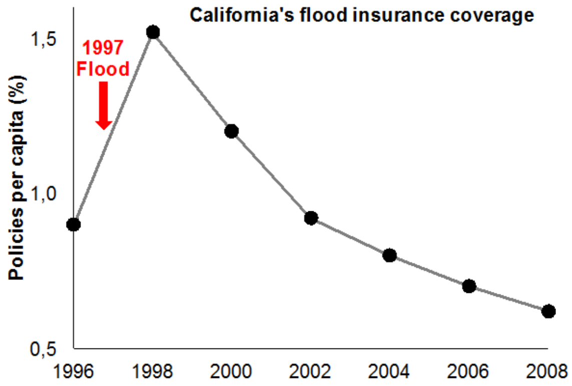
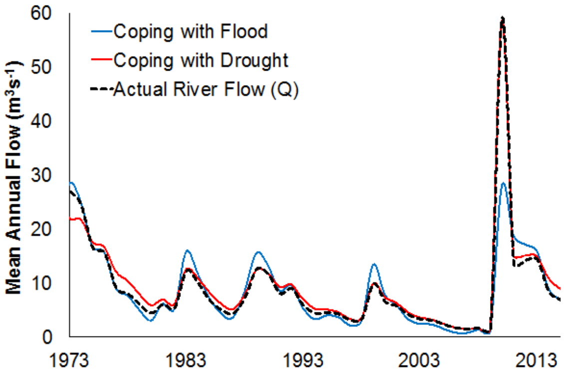


Figure 4: Changing memory and preparedness. Flood insurance coverage in California, which peaked after the 1997 Central Valley flood, and then decayed over time (data from Hanak, 2011). Note that in the same period policies per capita in the entire USA were essentially stable (Hanak, 2011).


60
50
40
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Mean Annual Flow (m^3s^{-1})
1973
1983
1993
2003
2013
Coping with Flood
Coping with Drought
Actual River Flow (Q)

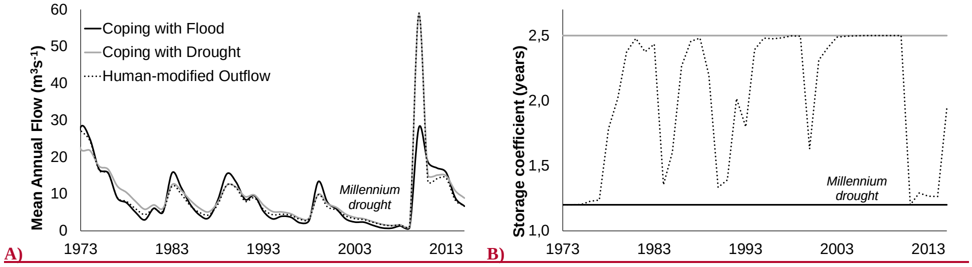

Figure 5: Example of ~~modelling~~ flood-after~~ and~~ -drought~~ in the Anthropocene~~. ~~The diagram shows the result of a model run: actual river~~ A) Human-modified outflows (~~black dash~~dotted line) that result from changing ~~norms in reservoir management~~storage coefficient (Panel B) between the values aiming to cope with flood (black continuous line) and aiming to cope with drought (grey line). Annual streamflow data the Brisbane River upstream the Wivenhoe reservoir were as inflows. ~~operation rules aiming to better cope with flood (blue line) and operation rules aiming to better cope with drought (red line).~~

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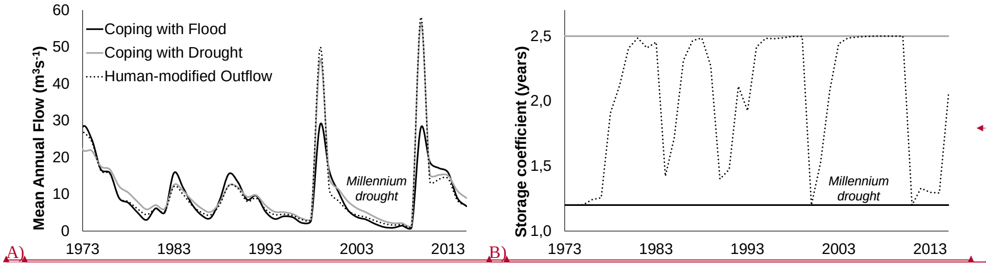

Figure 6: Example of drought-after-flood. A) Human-modified outflows (dotted line) that result from changing storage coefficient (Panel B), between the values aiming to cope with flood (black continuous line) and aiming to cope with drought (grey line). Annual streamflow data the Brisbane River upstream the Wivenhoe reservoir were as inflows.

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Table 1. Summary of time varying variables of the stylised model and initial conditions used in the experiment presented here.

	Units	Description	Type	Initial conditions
M_f	[.]	~~societal~~ flood memory ~~of floods~~	state	1
M_d	[.]	~~societal~~ drought memory ~~of droughts~~	state	1
Q	[L^3/T]	~~actual river~~human-modified out~~-~~flow	state	5 m^3s^{-1}

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Table 2. Summary of time invariant parameters of the stylised model and value used in the experiment presented here.

	Units	Description	Values
k_f	[T]	storage coefficient to cope with flood	1.2 y
k_d	[T]	storage coefficient to cope with drought	2.5 y
μ	[1/T]	memory decay rate	0.06 1/y
α	[T]	overflow coefficient	10 y
β	[.]	bias parameter	3
$Smax$	[L^3]	maximum reservoir storage	10^8 m^3

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