Title: Weathering water extremes and cognitive biases in a changing climate

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Abstract: Climate change is leading to increasing hydrological extremes and quicker shifts between wet and dry extremes in many regions. These extremes and rapid shifts put pressure on reservoir operations, decreasing the reliability of water supply, flood control and other reservoir benefits. Decision-makers across all levels, from reservoir operators to flood plain residents, turn to heuristics to simplify decisions when faced with complexity and uncertainty, resulting in cognitive biases or systematic errors in decision-making. While cognitive biases are not new, climate change is exacerbating their impact for two reasons: 1) heuristics, just as infrastructure, are based on experience with historic conditions; 2) fragilities created by these cognitive biases can go undetected until extreme events occur. If not acknowledged and managed, these cognitive biases can lead to catastrophic failures of reservoirs and other infrastructure. To minimize risk of such catastrophic failure, we propose a multi-level approach to flood and drought management, one that strikes a balance between centralized and decentralized approaches. Such an approach is better able to cope with uncertain and changing conditions because it creates overlaps and diversity, which can respond to a wide range of conditions and builds checks and balances that mitigate cognitive biases latent in various decision-making units.

The 2011 Brisbane Flood: Cognitive Biases at Multiple Levels of Decision-Making

In January 2011, Brisbane, home to 2.5 million people and the capital of Queensland, Australia flooded so catastrophically that a million people had to be evacuated. It was the most severe flood event in over a century in Brisbane and Australia's most expensive natural disaster to date [1]. Brisbane, built in the floodplain of the Brisbane River, is no stranger to flooding [2,3]. Intense summer monsoon rainfall is common in Queensland, particularly during the La Nina phase of ENSO [4]. The Somerset Dam was constructed in 1953 on the Stanley River (a tributary to the Brisbane River) to mitigate flooding and increase water supply reliability; later, the 1974 flood strengthened support for the planned Wivenhoe Dam on the Brisbane River [2]. With the construction of the Wivenhoe Dam the city of Brisbane was considered flood proof [5]. The January 2011 flood was the first large flood to test the dam. How did the Wivenhoe Dam fail its first test?

With the flood crisis in the rearview mirror, attention then turned to why and how such a disaster could have occurred. While several days of intense rainfall was clearly a factor, the flood operation decisions at the Wivenhoe and Somerset Dams were also called into question. Causes and culpability were debated in the Queensland Floods Commission of Inquiry [6], the media [1,7], and the courts [8]. The debate centered around dams and the dam operators [2]. Ultimately, the court found that the flood operations engineers, though with no malintent, failed to fully comply with the Flood Control Manual by disregarding forecast information and neglecting to lower reservoir levels below Full Supply Level (the water supply volume) in advance of the flood wave [8]. But why would the engineers make risky decisions in opposition to the Flood Control Manual?

At the center of the ruling was the question of how the flood operation engineers weighed information including observed rainfall, forecasted rain, and the recent drought. Like many reservoirs globally, Somerset and Wivenhoe Dams provide water supply storage for the Brisbane metropolitan region, in addition to their role in flood control, and these two objectives are in tension. Rules and regulations specify how these tradeoffs should be made but reservoir operators exercise their discretion within the bounds of these rules and can, as seen in the Brisbane case, violate them. The engineers with much to lose and nothing to gain in these decisions were not acting rationally in violating the flood control manual. In this they are not alone; people commonly use heuristics to simplify complex decisions particularly when operating under time constraints and uncertainty [9,10]. These simplifying heuristics result in cognitive biases (Box 1) or systematic errors in decision-making. The 2011 flooding of Brisbane, Australia occurred at the end of the decade long Millennium drought, a period in which dam operators struggled to meet water supply objectives and flood control was back of mind. We posit that this experience may have led to a cognitive bias affecting decision-making during the 2011 flood. That is, the operators' recent experience with drought may have prompted them to under-weight the risk of extreme flooding and over-weight the risk of water supply deficit. This bias toward recent, easier to recall, experiences when assessing probabilities is referred to as availability bias [9]. Availability bias is one of several cognitive biases that may shape decision-making in reservoir operation and, more broadly, flood and drought management (Box 1).

The perils of cognitive biases are not exclusive to dam operators. The bias that the city of Brisbane is flood proof became widely shared among the general public after construction of the Wivenhoe dam, although this was only an illusion in hindsight [5]. Theory suggests that such a false sense of security can lead to complacency and gradual withering of intangible societal-level capacity that plays a critical role during emergencies [11–15]. This may have been the case in Brisbane. With this collective sense of (perceived) flood security came decades of expansion into the flood plain, simultaneously reducing natural flood control infrastructure downstream of the dam and increasing the population at risk [2]. As observed in other cases, the success of controlling variability through large centralized infrastructure (e.g., reservoirs) reduced the incentive to maintain capacity to manage such variability throughout the watershed [16,17].

The case of Brisbane is illustrative but not exemplary. There are other examples of recent experiences shaping reservoir operators' decisions from maintenance (e.g., Oroville Dam [18]) to releases (e.g., Lake Mendocino, see Box 1). Further, there are numerous cases where the broader public's memory or awareness of hazards decreases as reservoirs and other large-scale infrastructure control variability [17,19,20]. Understanding the implications of both biases—dam operators' bias toward more "available" experiences and societal-level bias toward the myth of hazard immunity—and the way these two biases interact with infrastructure built to control floods and droughts is particularly important in the context of climate change adaptation. There is increasing evidence that climate change is intensifying extremes and accelerating the shift between dry and wet extremes, worsening the perils of these two biases [21–24]. Here we review the challenges of climatic change and decision-making biases for flood and drought management, discuss the emerging technical and policy responses, and make the case for a whole system perspective.

Box 1 – Cognitive biases in dam operation

As in the 2011 Brisbane flood, the combined cognitive biases of both operators and floodplain society may result in unpredicted catastrophic events [1]. Let us look at another multi-purpose reservoir to explore the possible cognitive biases of operators. Lake Mendocino Reservoir (Coyote Valley Dam), on the East Fork of the Russian River in Mendocino County, California, provides water supply and flood control. As seen in Fig. Box 1-1, the operator did not strictly follow the operational rule in the transition period (March to May) from the flood season to the dry season to store excessive water (refer to the observed reservoir storage (black line) in the water year 2007). This anomalous operation may have been in response to previous drought and may be helpful for mitigating water shortage but there is a chance of heavy rain during the transition period. To avoid increased disaster risk, it is necessary to know how the operator's memory of the previous disaster affects their decision-making behavior in reservoir operation. We developed a simple reservoir operation model and conducted scenario analysis to assess how different types of cognitive biases influence the decision-making of a reservoir operator.

In the model, the reservoir operator controls the discharge rate in consideration of the storage level (state variable) and the operational rule (target) using a proportional–integral–derivative (PID) controller, which is widely used in engineering systems [25]. PID controller is a kind of feedback control that uses the output of the system as a part of its control. PID controller consists of three controls: 1) Proportional deviation of state variable from the target (P control), 2) Integral deviation of state variable from the target (I control), and 3) Derivative (rate of change) deviation of state variable from the target (D control).

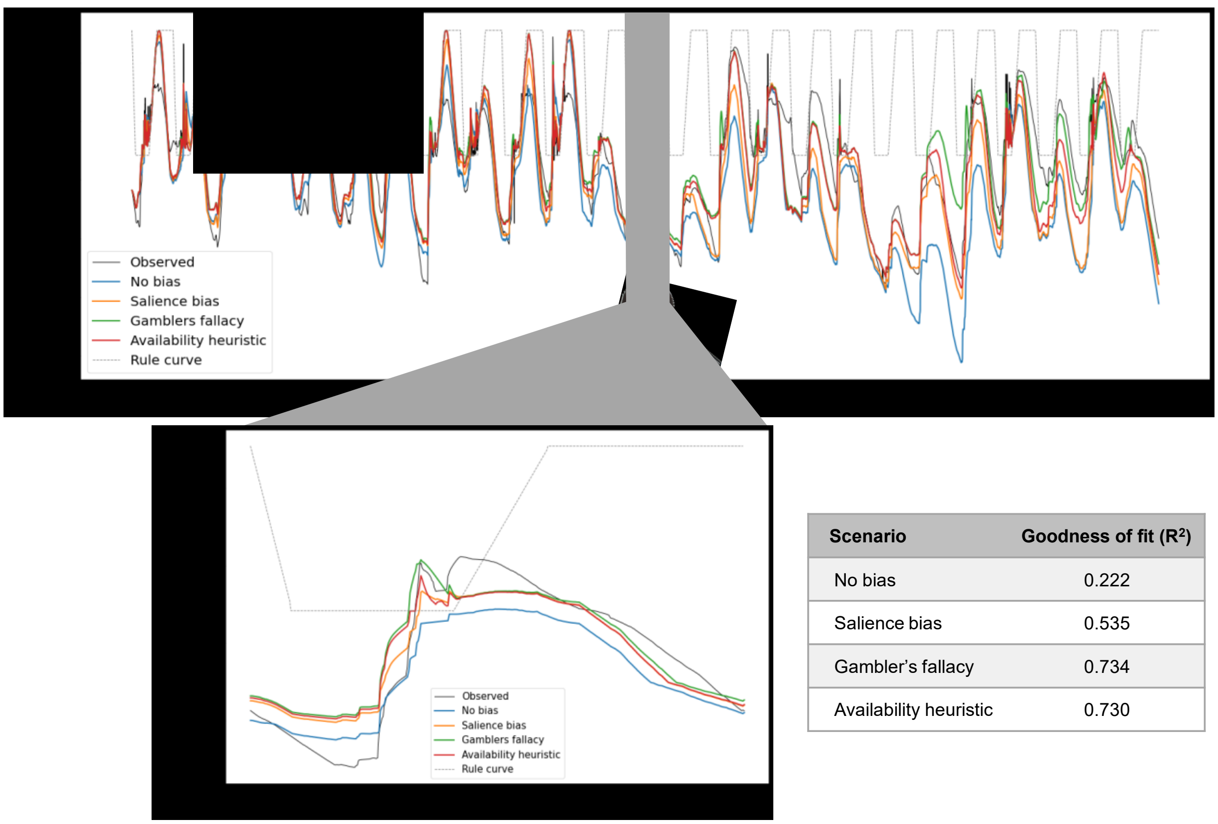
We created four scenarios concerning the operator's bias with different configurations of the PID controller (Box Table1-1). As the baseline scenario, we assume that the operator is perfectly rational (no bias) and their decisions are not affected by their past experiences. Because the operator strictly follows the operation rule, the perfect rationality scenario uses only P and D control. There are numerous types of cognitive biases documented in the psychological literature [26–28]. We selected three representative types that are most relevant to disaster memory: Salience bias, Gambler's fallacy, and Availability bias. For the following three scenarios, we set the same period and implemented I-control as the accumulated past disaster damages (either flood or water shortage) according to the assumption of each scenario, in addition to P and D control. **Salience bias** predisposes individuals to focus on remarkable and emotionally striking events [29]. For the Salience bias scenario, we posit that the operator believes that the most severe disaster in the past would happen again. Salience bias scenario uses the relative damage of the most severe disasters to inform the I-control. Under the **Gambler's fallacy** individuals believe that the probability of a random event in the future is influenced by that type of event in the past [30]. In the Gambler's fallacy scenario, the operator believes that the most frequent disaster in the past would happen again. This scenario uses the relative damage of the most frequent disasters as I-control. With **Availability bias** people tend to heavily weigh their judgments toward the latest information [31]. In the Availability bias scenario, the operator believes that the most recent disaster would happen again. This scenario uses the relative damage of the most recent disasters as I-control.

The simulation results of each scenario and the goodness-of-fit compared to the observed data are shown in Box Figure1-1. Here we are not aiming to prove a specific cognitive bias is present, but instead explore what types of biases provide a better fit for observed patterns in Lake Mendocino. Perfect rationality shows the lowest goodness-of-fit, which implies the operator was least likely to be strictly following the operational rule.

Gambler's fallacy and Availability bias return plausible explanatory power, indicating that the operator is likely affected by the most frequent and recent events in the past. These findings do not mean that one specific type of cognitive bias governs the decision-making of operators. Reservoir operation can be affected by the combination of different types of cognitive biases. Instead, these results demonstrate the importance of considering cognitive biases in reservoir operation.

Box Table1-1. Reservoir operator's biases

Cognitive Bias	Assumption of Operator's behavior	PID controller
Perfect rationality (No bias)	The operator does not care about past disasters and strictly follows the operation rule	P and D
Salience bias	The operator believes that the most severe disaster in the past would happen again	P, D, and I (accumulated damages of severe disasters in the past)
Gambler's fallacy (Frequency illusion)	The operator believes that the most frequent disaster in the past would happen again	P, D, and I (accumulated damages of frequent disasters in the past)
Availability heuristic (Recency illusion)	The operator believes that the most recent disaster would happen again	P, D, and I (accumulated damages of recent disasters in the past)



Scenario	Goodness of fit (R^2)
No bias	0.222
Salience bias	0.535
Gambler's fallacy	0.734
Availability heuristic	0.730

Box Figure1-1. Simulation results of water storage levels according to different types of reservoir operator's biases of Lake Mendocino, CA (1995~2020) and goodness-of-fit of each scenario.

Weather Extremes and Reservoir Operation: Unintended Consequences

Climate change is driving shifts in temporal and spatial hydrological patterns. Increases in extreme high precipitation are projected under climate change (5–10%/°C) [23,32,33]. Higher temperatures have the potential to drive the acceleration of the hydrological cycle; however, the projected increase in global mean precipitation is modest (around 3%/°C) [34] because the increasing extreme high precipitation is offset by an increase in the number of dry days [35] and the frequency of dry spells [36]. Further, increasing temperatures raise evapotranspiration, exacerbating drought and further stressing water supply systems [37,38]. Due to their non-linear processes, watersheds themselves have the potential to amplify variability inherent in precipitation [39]. Even within particular regions the effect on individual rivers varies. For example, Blöschl et al. [40] found that changes in mean flood discharge varies between an 11 percent increase and a 23 percent decrease within Europe between 1960 and 2010. Beyond intensifying extreme precipitation, increasingly quick shifts between dry and wet extremes, referred to as Weather Whiplash, are projected in some regions (e.g., California, U.S. and the Mid-Western, U.S.) [21–24,41]and observed in others (e.g., Southern South America and Northern Asia) [42].

Storage, both natural and constructed, helps to balance periods of extreme high and low precipitation. Increasing extreme drought and extreme wet weather require more storage space to meet water supply and flood control objectives. Yet, the available storage volume can only serve one purpose at once. Declines in snowpack with rising temperatures [43,44] and groundwater due to unsustainable pumping [45,46], lower natural storage, putting greater pressure on reservoirs. Snow drought further exacerbates the tension between water supply and flood control storage in snow dominated systems [18]. Reservoirs play a key role in mitigating hydrological variability, but their design and operating rules assume historic hydrological conditions, which in many regions is no longer a valid assumption [47]. Traditionally, operational plans, for reservoirs that serve water supply and flood control objectives, are developed based on historical streamflow, current and projected demand, and past performance of operational decisions. While this approach to reservoir operation has been historically effective, the ability to meet both water supply and flood control objectives declines as extremes intensify [48]. This is due to both that the infrastructure and operations have been fit to past hydrological patterns, and that operators, consistent with other decision makers, draw on heuristics to simplify complex decisions and these heuristics are constructed from past experiences [20,49].

How and when to change reservoirs and their operating rules in response to changing conditions is not a straightforward question. The potential for reservoir expansion or addition of reservoirs is, in many regions, limited by cost, space, and ecosystem concerns so attention is directed to changes in operations. Adaptive reservoir operations are one response that aims to improve performance without changes to physical infrastructure, by incorporating current observations and forecasts to adjust system operations in response to changing conditions [50]. Over the past decade, research has demonstrated the value of adaptive reservoir management across various climatic and socio-economic settings [48,51,52]. By institutionalizing adaptive controls based on current observations and forecasts, this approach can also inhibit the availability bias by explicitly guiding how operators should incorporate new information.

However, there are limits to the amount of additional variability that adaptive operations can enable reservoirs to mitigate. For example, in the Russian River, located in Sonoma and Mendocino counties in Northern California, where adaptive reservoir operations are already in place, extreme drought is still resulting in water supply reductions [53]. This suggests that additional layers of capacity or infrastructure should be in place across the watershed to absorb residual variability left by reservoirs. Building and maintaining such capacity throughout the watershed is therefor of critical importance to resilience at system-level. More importantly, components of such capacity are often interdependent with the centralized infrastructure and one another, affecting system-level outcomes in subtle ways. For example, although adaptive operation of reservoirs can help to control additional variability, this extra margin of adaptability (and thus greater stability) can come at the cost of reduced learning opportunities by individuals and groups distributed throughout the watershed, thereby amplifying the myth of hazard immunity in ways that undermine system-level resilience in the long run (Figure 1). Neither the problems nor the solutions are solely in the realm of reservoirs. Instead, watersheds are complex evolving systems comprised of interacting components governed through regulatory feedback. A whole system perspective is therefore needed to both diagnose the problem and identify solutions.

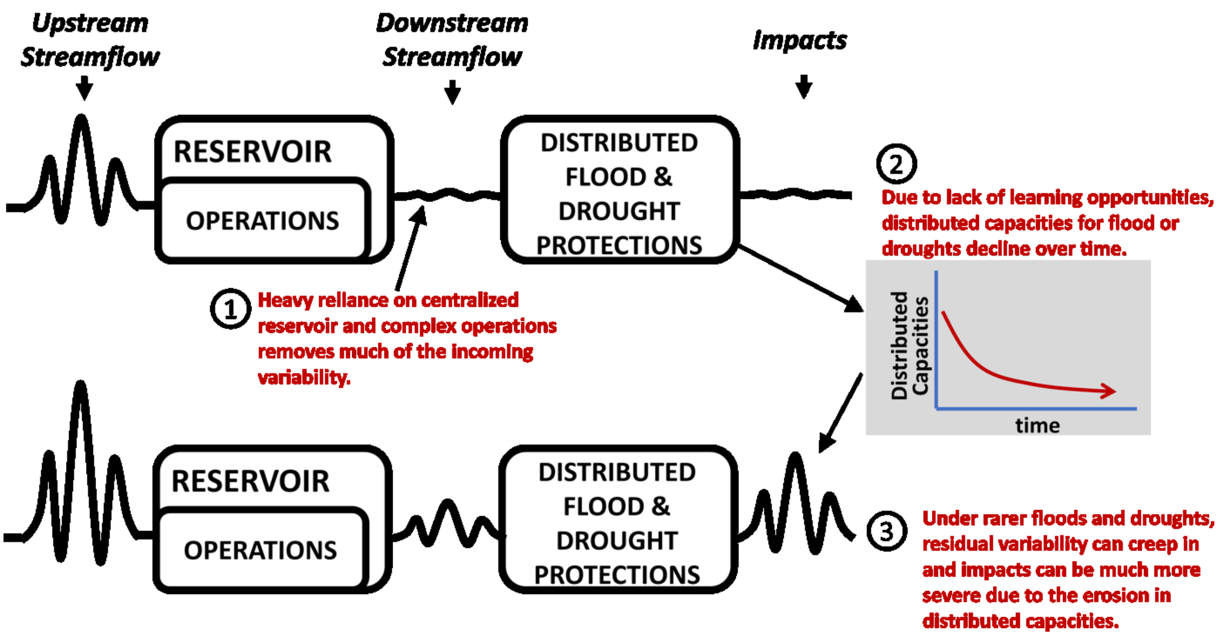


Figure 1: Tradeoffs in capacities between centralized infrastructure and distributed infrastructure

A Systems Perspective: from Reservoir to Coupled Infrastructure System

A reservoir is part of a larger whole—an interdependent system of watershed and society with many interacting components that respond and adapt to either too much or not enough water (Figure 2). Here we interpret the qualitative behavior of the system by applying the lens of coupled infrastructure system (CIS), a systems perspective that views the larger whole as a constellation of several different types of infrastructure or capacities that are distributed and adapted to deal with recurrent disturbances [54]. These infrastructure types include hard infrastructure, natural infrastructure, soft infrastructure, human infrastructure, and social infrastructure. The various elements of the watershed and society belong to these different types of capacities and these elements become well-adapted over time to instill robustness to typical disturbances. In the context of floods and droughts, reservoirs represent a centralized hard infrastructure and are one way to manage streamflow variability in the overall system. There are other elements in the system that have capacity to manage drought and flood periods. For example, the skills and knowledge of reservoir operators (human infrastructure) and the reservoir operating rules they follow (soft infrastructure) can influence the impacts of floods and droughts. The capacity of floodplain residents to organize collective action (social infrastructure) in sandbagging, evacuation, and advocating for rule changes can affect flood impacts. Similarly, farmers' cooperation for water conservation and sustainable use of water resources (social infrastructure) can mitigate drought impacts. Policy, from local to federal, is also social infrastructure that influences whether and how these distributed practices are adopted and maintained [55,56]. Wetlands, rain gardens, and re-opening flood plains (natural infrastructure) are distributed approaches for managing flooding [57,58]. At the system-level, these different capacities work in concert to make the system robust to a set of disturbances, and there are multiple decision-makers involved in the process to influence how these capacities are modified (Figure 2).

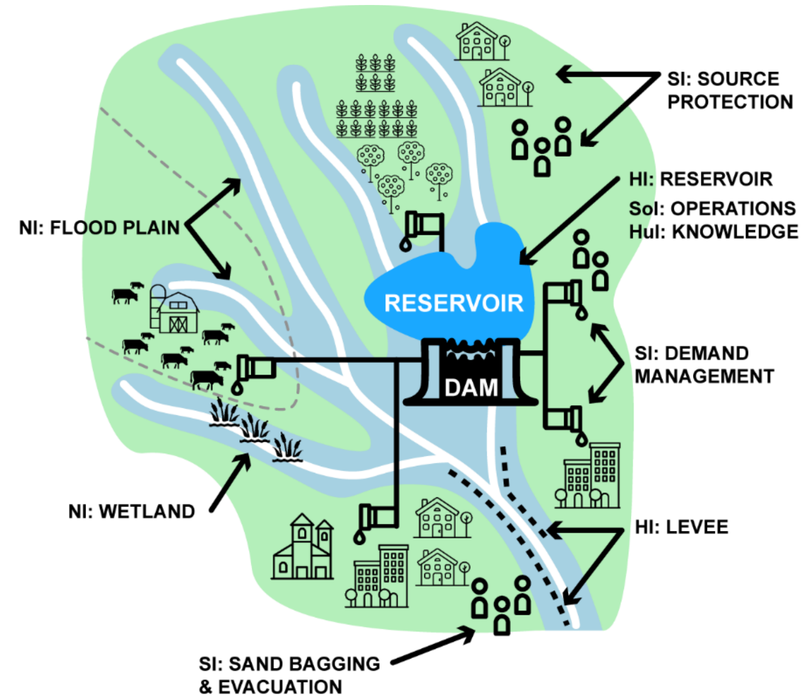


Figure 2: CIS in the watershed. NI = Natural Infrastructure or the environment (e.g., wetlands); HI = Hard Infrastructure or the built environment (e.g., reservoirs & levees); SoI = Soft Infrastructure or instructions for use of other types of infrastructure (e.g., reservoir operating rules), HuI = Human Infrastructure or skills and knowledge (e.g., expertise of reservoir operators), SI = Social Infrastructure or the capacity to organize collective action (e.g., cooperative water conservation).

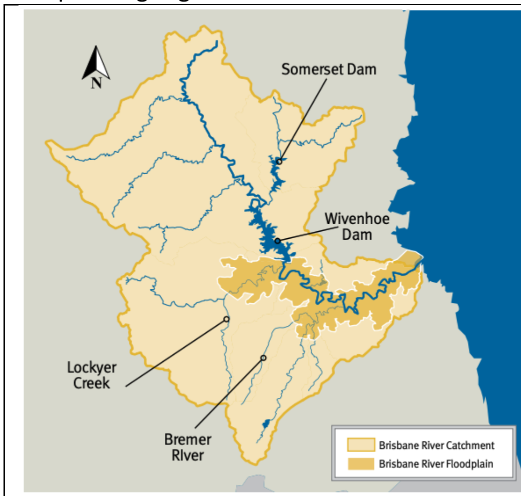
Yet the system can still be fragile to different types of disturbances. Theory suggests that tradeoffs often arise among these different types of infrastructure across multiple scales [59]. Increasing the success of one infrastructure in mitigating a particular type of hydrological variability can undermine the coping capacity present in other types of infrastructure or the capacity of the same infrastructure to deal with a different variability (Figure 1). For example, dam operators and their operating rules well-adapted to drought conditions can undermine the human infrastructure for dealing with flood conditions in the form of cognitive biases such as the availability bias [9]. In addition, such tradeoffs in fragility are often hidden until revealed by catastrophic failures, especially when adaptive feedback controls are present. For example, heavy reliance on hard infrastructures such as centralized reservoirs and levees or increased complexity in their operational rules can help to filter out additional variability and, thus, achieve greater stability [17,20]. However, this extra margin of stability reduces opportunities for individual and social learning and might lead to complacency, erosion of collective memory about floods (a form of cognitive bias), and loss of social capacity to organize voluntary group actions for response and recovery (social infrastructure), resulting in greater vulnerability to rarer floods in the long run. For example, in the US, a program to buy back land to re-open flood plains (natural infrastructure) along the Mississippi and Missouri Rivers, was counteracted by social forgetfulness and increased downstream development in long protected flood plains [60]. Such tradeoffs can also arise with respect to droughts. The reservoir effect is another socio-hydrologic phenomenon that describes instances where over-reliance on water infrastructure increases water dependence and demand, and therefore increases the potential damage from water shortages [61]. The reservoir effect is a particular case of the broader safe-development paradox in which reduced risk increases settlement in vulnerable areas, resulting in increased damage [62]. This phenomenon of highly effective control of variability eroding capacity to manage different frequencies or types of shocks extends both to other infrastructure systems [63] and to social and ecological systems broadly [11,15]. Critically, this eroded capacity is amplifying vulnerability to increasingly extreme floods and droughts. However, rebuilding this capacity is also an opportunity, particularly in places with limited possibility for more robust reservoir storage. To sum it up, some fragilities are inevitable in a complex watershed system because of the inherent interdependencies and tradeoffs. Resilience lies in systematically managing such tradeoffs through proactive sensing and anticipatory management, and in ways that mitigate cognitive biases of the infrastructure operators and the general public.

With this systems perspective, we can now interpret the flooding of Brisbane in 2011 as a coupled infrastructure system (Box 2). A key insight is that the catastrophic outcome of the event cannot be attributed only to the natural hazard, the reservoir capacity (hard infrastructure), or the biases of dam operators and agencies (human infrastructure). Because of the societal-level bias about flood immunity and the economic and population growth in Brisbane since the 1970s, a large share of the population in the region were either new to the area or of a younger generation who did not directly experience the 1974 flood [2]. It is likely the case that Brisbane's social infrastructure of collective flood memory eroded substantially by 2011, as suggested by the fact that the general population chose to expand and settle in the floodplains [1,64]. This collective forgetfulness and associated encroachment on the floodplains, coupled with the availability bias of the dam operators, likely set the stage for the catastrophic outcome of the 2011 flooding [65,66]. Awareness of the potential for cognitive biases to shape decision making in reservoir operators and the general public could have alerted regulators or other decision-makers for the potential for catastrophic failures; further, a coupled infrastructure systems approach to managing floods and droughts could have identified ways to reduce the consequences of reservoir failure.

Box 2 – A System Perspective on the 2011 Brisbane Flood

The catastrophic 2011 flooding of Brisbane unfolded through the interaction of hydrological events, reservoir design and operations, land use change, and regional community flood awareness. This web of interactions requires a broad systems perspective capable of capturing an interconnected system of social, hydrological, natural, and technological components in which a reservoir and its operating organization are embedded.

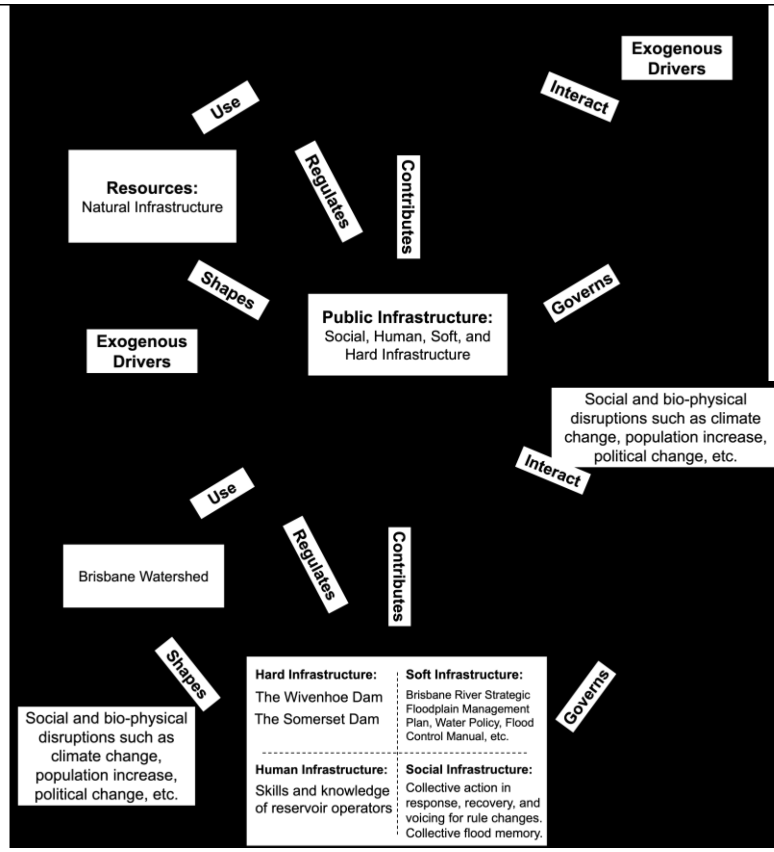
We adopt the lens of CIS to the Brisbane watershed (Box Figure 2-1). The CIS is an approach characterized by four generic components (resource, resource users, public infrastructure, and public infrastructure providers), their relationships, and how these components and relationships influence the capacity of a CIS to withstand internal stresses or external disturbances (Box Figure 2-2a) [68]. These components represent different types of capacity or infrastructure (hard infrastructure, natural infrastructure, soft infrastructure, human infrastructure, and social infrastructure) that are distributed and fine-tuned to deal with recurrent disturbances [54]. Below, we apply the CIS lens to the Brisbane case by describing how different components and capacities that reside in Brisbane's watershed can be interpreted in terms of the CIS components. We also map the linkages among them (Box Figure 2-2b).



Box Figure 2-1. Brisbane River Catchment and Floodplain [67]

- **Resource (i.e., Natural Infrastructure):** The Brisbane watershed is the resource in the CIS. It is part of the Brisbane River catchment, which spans approximately 13,570 km^2 and is home to the largest river in South East Queensland [69]. Approximately half of the catchment drains into the Wivenhoe and Somerset Dams, providing the primary source of water supply for communities located in the region. The Brisbane River floodplain is the most flood impacted area in Australia [67]. Land use in the Brisbane River catchment includes natural land cover (~24%), irrigated agricultural and grazing (~15%), intensive development (e.g. residential, industrial; ~58%), and surface water (~2%) [70].
- **Resource Users (i.e., Social and Human infrastructure):** Resource users live within the Brisbane River floodplain (more than 280,000) or receive water supply from the Brisbane River. Among them, around 130,000 are living in highly vulnerable areas [67]. Brisbane is economically diverse (e.g., finance, technology, transport, mining) and the largest of the cities receiving water from the upstream reservoirs. Outside of Brisbane the region is largely rural. The agricultural sector, including vegetables and livestock are an important part of the economy [71]. Here, human infrastructure includes individuals' knowledge and preparedness regarding flood emergencies. Social infrastructure includes social norms and collective action that play a critical role during disaster relief and recovery situations.
- **Public Infrastructure**:
    - **Hard Infrastructure**: The Wivenhoe and Somerset Dams are the primary water supply sources for the Brisbane metropolitan area, mitigate flooding and generate hydropower [72]. Somerset Dam was commissioned in 1959 and is a mass concrete dam. It has a capacity of 721,000 ML with 380,000 ML dedicated to water supply storage (the full supply level of FSL). Wivenhoe Dam was completed in 1984 and is an earthen and rock dam with a concrete spillway. It has a capacity of 1,970,000 ML with 1,165,200 ML allocated to water supply storage [72].

- **Soft infrastructure**: Institutional arrangements such as state and regional plans, and climate adaptation strategies define interactions between local and government sectors in the Brisbane watershed. Additionally, a review of flood resilience activities since the 2011 floods resulted in 2019, the Brisbane River Strategic Floodplain Management Plan. This plan aims to strengthen the flood resilience of the region including land use planning, disaster management, building controls and structural mitigation options [67]. Floodplain construction standards apply throughout the floodplain but there is no requirement for flood insurance.



Box Figure 2-2. a) The CIS Framework that outlines four generic components of a CIS (resource, resource users, public infrastructure, and public infrastructure providers), their relationships, and how these components and relationships influence the capacity of a CIS to withstand internal or external disturbances b) Brisbane flood catchment through the lens of CIS Framework

- **Public Infrastructure Providers:** Relevant public agencies are the public infrastructure providers. Water policy is the responsibility of state government in Australia while local governments are responsible for water supply, stormwater management, and wastewater collection and treatment [73]. Starting in 2005, regional planning entities were given the responsibility of land use planning and conservation. Prior to 2000, a regional water board owned most water infrastructure in Southeast Queensland where Brisbane is located. In 2000, the board was commercialized as the SEQ Water Corporation (Seqwater) [73]. Seqwater operates Somerset and Wivenhoe Dams and follows the approved Flood Mitigation Manual and other operational documents. The operation of Somerset and Wivenhoe Dams are subject to federal regulation under the Water Supply Safety and Reliability Act of 2008 and changes to the flood mitigation manual require approval of the Minster [72].

Preparing for a New Abnormal

While cognitive biases have long been present in infrastructure operation and the way the general public thinks about natural hazards, the vulnerability caused by these cognitive biases can remain hidden until extreme events occur. Centralized infrastructure has performed well, so well in fact that it has reduced impacts sufficiently to lower the incentives to develop and maintain all types of decentralized infrastructure [16,61,74] (Figure 1). This is in part a product of societal scale cognitive bias.

The combination of intensifying hydrological extremes, operator cognitive biases, and erosion of distributed capacity compounds vulnerability. Existing hard infrastructure, designed to control historic hydrologic variability, will not be able to attenuate all increased variability, impacting water users and flood plain residents. More frequent hydrological extremes under climate change will expose more of these vulnerabilities – the hard way.

We suggest that preparing for a new abnormal in such changing environments requires a multi-level approach to flood and drought management, one that strikes a balance between centralized and decentralized approaches. This feature, referred to by many as polycentricity [75,76], is characterized by having multiple, overlapping centers of oversight and decision-making at higher and lower organizational levels, e.g., the presence of flood or drought mitigation strategies at multiple levels ranging from household and community levels to local and federal agency levels. Systems with this multi-level feature are known to be better able to cope with uncertain and changing conditions because of overlaps and diversity in response [75,77]. In flood and drought management, it signifies maintaining diversity in response and function through a balance among different CIS components or between centralized infrastructure (e.g., reservoirs and levees) and coping capacities distributed throughout the watershed (e.g., flood plain wetlands and organizational capacity for water conservation). Applying this way of thinking to management, in the long term, can help to build adaptability for the unknown and unknowable future.

At the centralized level, increasing storage capacity of reservoirs through expansion (e.g., heightening of Roosevelt Dam on the Salt River [78]) or new construction can be a measure to reducing vulnerability. But this is infeasible or limited in many regions. Hard infrastructure, particularly large and centralized water infrastructure, have limited ability to adapt due their large scale, rigidity, and interconnections with other critical systems [79]. In absence of opportunities for new infrastructure development or modification of existing hard infrastructure, increasing the adaptability of reservoir operation rules, a soft infrastructure, can raise watershed system robustness [79–81]. Improved use of information and adaptive rules can make reservoir operations more agile, enhancing the centralized capacity to deal with fluctuating conditions [82,83]. The tradeoffs inherent in the CIS components, however, suggest that cautions must be taken with an over-reliance on adaptive operations of reservoirs.

Centralized approaches alone are insufficient as outlined above. A multi-level, polycentric effort is needed to promote and maintain complementary capacities across the watershed system. Measures such as effective public risk communication that reinforces collective flood memory, establishment of green or natural infrastructure distributed across the watershed, anticipatory land-use and hazard mitigation plans by local municipalities, household-level strategies such as elevating buildings, xeriscaping and drip irrigation, and voluntary group actions activated in times of emergency all work to generate overlaps and diversity in response [75]. This view is aligned with the observation that infrastructure design in a changing climate needs to shift from fail-safe to safe-to-fail. Fail-safe infrastructure is designed to avoid failure under specified operating conditions. Safe-to-fail infrastructure anticipates the potential for failure and designs to contain and learn from the impacts [84,85]. We agree with Ahern [84] and Kim et al. [85] that under a changing climate, infrastructure has an increased risk of failure and there is a greater need to prepare for that failure. In line with Yu et al. [75], we suggest that working across scales and space in the watershed not only increases redundancy but also diversity, increasing the likelihood that the system can respond to unanticipated types of shocks as well as increasing magnitudes of familiar shocks. For example, decentralized infrastructure systems also have the added benefit of increased flexibility due modality and its smaller scale can enable piloting of new techniques and technologies [86]. A polycentric system that manages extremes events through both large-scale hard infrastructure and capacities distributed throughout the system will be better positioned to weather accelerating climate change.

We also argue that polycentric approach creates checks and balances that mitigate cognitive biases latent in various decision-making units. Adaptive reservoir operation can provide an added benefit of preventing reservoir operators' availability bias by explicitly guiding how operators should incorporate new information. Operational policies of centralized infrastructure can be made more adaptive to alert operators to potential biases, particularly when conditions change rapidly. To address cognitive biases in the general public, we can invest in education to keep the awareness of natural hazards alive in an environment where we have minimized their impacts. The presence and visibility of diverse coping capacities at the decentralized level can also help to prolong local knowledge of flood and drought events embedded in individual and collective behaviors. Acknowledging cognitive biases helps anticipate their consequences and find vulnerabilities not yet revealed by extreme events. Additionally, research is needed to understand how the interaction of cognitive biases with hydrological extremes varies across hydroclimatic, institutional, and cultural settings, and to inform the design of interventions. Synthesis across cases that allows for control of some variables (e.g., seasonal streamflow patterns) while deliberately varying others (e.g., rules for water management) is a promising way to build understanding.

The challenge of an increasingly variable and extreme climate extends beyond hydraulic infrastructure. While climate change is in many respects water change [87], it will impact infrastructure across sectors, revealing long existing cognitive biases. If not acknowledged and managed, these cognitive biases can lead to catastrophic failures of reservoirs and other infrastructure. Conventional infrastructure planning and management focuses on technical and economic considerations, and seldom considers human cognition and biases, polycentric control, and feedback amongst these features of a complex system. As climate change plays out, we will need all available tools at our disposal to maintain critical services from flood control and water supply to power and transportation. Harnessing these tools requires collaborative interdisciplinary research and practice that can identify processes that span disciplinary boundaries and design interventions that target the system not merely its components. While the 2011 Brisbane flood is one case, given the pace of climate change already observed and the further changes projected, this type of failure could become more common as infrastructure is pushed beyond its design conditions if we do not act.

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CRediT author statement

MG, DY and MS conceptualized the paper and acquired funding, SP created the software, BMI conducted literature review, MG, DY, SP and PY created visualizations, all authors wrote, reviewed, and edited the paper.

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