Forum

# Review of Approaches and Recommendations for Improving Resilience of Water Management Infrastructure: The Case for Large Dams

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**DOI:** 10.1061/(ASCE)IS.1943-555X.0000370

## Introduction

A Task Committee (TC) on Infrastructure Impacts of Landscape-Driven Weather Change of the American Society of Civil Engineers (ASCE) was formed during 2012–2013. At that time several events related to improving infrastructure resilience for water management were front-page news across the nation. For instance, around 2009 the Tennessee Valley Authority (TVA) reported that the height of four of their dams would be raised by more than 1 m (Hydroworld 2009). Although the scientific reasoning behind the height increase was not clearly known, media reports suggested that the projected increased risk of greater flooding from global climate models (GCM) may have driven this decision. It should be noted that despite its wide use of adaptation policies, there exists considerable uncertainty and debate around the use of GCM projections for large-scale infrastructure for water management (e.g., Hossain et al. 2012; Kundewicz and Stakhiv 2010, Anagnostopoulos et al. 2010; Stephens et al. 2010, van Haren et al. 2012; Hourdin et al. 2016). Other studies, such those on stormwater infrastructure, also show that the use of GCMs may lead to a design mismatch (Moglen and Vidal 2014).

At the forefront of this ASCE TC is the resilience of large infrastructure, particularly large dams and artificial reservoirs that form the cornerstone of most regulated river systems of today. An important consideration for this study is that if it is cost prohibitive to fortify a large system comprising dams in a river basin, would it be possible to design these systems and their upgrades to fail gracefully? Graceful failure is not a new concept (Hossain et al. 2015a; the first report of this TC). Many dams have fuse plugs in redundant spillway systems that are designed to fail when a shock flood wave occurs upstream. This concept, however, is subject to the availability of open land downstream that can be inundated with floodwaters. The ASCE TC recently conducted a survey of experienced water managers regarding the critical issues facing the nation's large water infrastructure (Hossain et al. 2015b). This survey was the second in the series of reports produced by this TC. It revealed that the engineering profession may need greater academic–practitioner collaboration to develop more use-inspired curriculum for future engineers who will have to solve interdisciplinary problems not experienced before (Hossain et al. 2015b). Therefore, if historical management practices prioritized either water quality or quantity over the other, moving forward, water management will have to consider and balance both. For example, the eutrophication of water bodies near agricultural land is traditionally treated solely as a nonpoint pollution runoff problem rather than also as a water management issue. Practitioners now recognize that both aspects need to be addressed jointly in management practices to address emerging challenges. Many practitioners also feel that the emergence of new contaminants or changes to water quality due to varying quantity brought by a drought or a flood will likely add to the cost of water delivery systems—an issue that is yet to be included in water management research and practice.

During the October 2015 flooding in South Carolina, a record amount of rainfall caused mass disruption for the entire state. However, the biggest casualty was not life or property. Rather, it was the disruption of freshwater supply and the wastewater treatment system that were knocked out in the immediate aftermath of the flooding (Good 2015). This resulted in a shortage of safe drinking water for large sections of the state. The next big casualty was the increased vulnerability of 36 large dams in the state that were overtopped during the flooding (Good 2015). These dams, according to the American Society of Dam Safety Officials (ASDSO), were already in need of repair and posed a high risk downstream. These events suggest that trying to make one entity of an infrastructure system more resilient (e.g., power distribution, transportation,

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or flood control) will not be adequate in the future. The entire system, including reliable transportation of goods, supply of energy and water, as well as a cleaner and safer environment, will need to be made smart as a whole. Thus, for the design and maintenance of water management infrastructure in light of extreme climate events, it would be prudent to explore what other engineering communities have already implemented for improving resilience. In this report, the TC reviewed literature on infrastructure issues from various related engineering disciplines to find ways to make them relevant for water management infrastructure. The findings of the literature review are reported below.

## Setting the Definition of Resilience

Although a definition of *resilience* was provided by this TC in its first report (see next paragraph), the current survey identified several other perspectives relevant to the definition of infrastructure. We highlight one here.

The first TC report provided the following definition (Hossain et al. 2015a): "A Weather-Climate Resilient Water Infrastructure is defined as an infrastructure that can to a degree anticipate or adapt and recover from external disruptions due to severe weather and climate, and carry on providing the essential services the infrastructure is designed for with managed interruption to non-essential services, while balancing tradeoffs among social (e.g., security), environmental, and economic factors."

According to an alternate definition from the review of the literature, "Resilience can be measured by the scale of challenge that the system can endure beyond normal demand, and in decision making, may be balanced against other factors by what is proportional, affordable and tolerable." (Hudson et al. 2012)

## ASCE History of Addressing Resilience Issues

Review of literature reveals that ASCE has been at the forefront of addressing water infrastructure resilience. As early as 1956, a Task Force on Spillway Design Floods was established by the ASCE that concluded that "for large major structures that would be subject to possible failure if the selected capacity were exceeded, there would be few instances, if any, where anything less than provision for the probable maximum flood can be justified" (Snyder 1964). Later, ASCE set up a TC on the Reevaluation of the Adequacy of Spillways of Existing Dams and produced a paper, "Reevaluating Spillway Adequacy of Existing Dams" (ASCE 1973). During the 1970s the key concern was the probable maximum flood (PMF) that currently serves as the mandatory design standard for many high-hazard U.S. dams. By default, the consideration of PMF in design indirectly added to the resilience of an infrastructure due to the unlikely probability of PMF being exceeded. Many researchers suggested that modifying dams to accommodate the PMF could be wasteful (e.g., Dawdy and Lettenmaier 1987). The focus then became prioritizing the dams that needed spillway upgrade more urgently than others. Graham (2000) provided an excellent historical overview of this issue and ASCE's leadership in addressing water infrastructure resilience. Despite the above research and recommendations there is still no unified building and operations code in the United States to address resilience in dam design. Rather, the practices recommended (Hossain et al. 2012, Table 2) are state-specific and based on the perception of risk and understanding of regional hydrology.

Graham (2000) also proposed an approach for assessing whether any structural retrofitting or upgrade to a dam was sound from an economic and loss-of-life perspective. This approach was designed to avoid costly overdesign in the name of a false sense of improved resilience. This approach is

"For each proposed modification designed to reduce or eliminate dam failure, compute:

1. Annualized Cost of the modification, $C_M$, (dollars).
2. Annualized Economic loss caused by flooding, $E_M$, (dollars).
3. Annualized Life loss caused by flooding, $L_M$, (number of lives).
4. Life loss from Construction spending (0.14 lives per \$100 million expended) and convert to annualized value, $L_C$, (number of lives).
5. Economic Benefits derived from modification, $E_B$, where $E_B = E_S - E_M$ (dollars).
6. Life Benefits derived from modification, $L_B$, where $L_B = L_S - L_M - L_C$ (number of lives saved).
7. Use Table 2 of Graham (2000) to reject or accept the infrastructure modification.

Note: For status quo: a. Annualized Economic loss caused by flooding, $E_s$ (dollars); b. Annualized Life loss caused by flooding, $L_S$ (number of lives)"

This approach outlined by Graham (2000) provides logic for addressing resilience issues, even those that are impacted by changing extreme events and climate. The increased use of physical model–based Probable Maximum Precipitation (PMP) and PMF to provide a framework for testing the sensitivity of large water infrastructure, such as dams, to anticipated changes in extreme events are recorded in many recent publications (Tofiq and Guven 2015; Yigzaw and Hossain 2015; Yigzaw et al. 2013). These provide the rationale for translating estimated changes in PMP and PMF into required modifications to spillway design.

In 1994, the National Research Council (NRC 1994) set up a committee to understand the limits of extreme weather events as they pertain to large water management infrastructure. Many such historical extreme weather events have been maximized by engineers as probable maximum precipitation (PMP) using ad hoc approaches. Because engineers design large infrastructure for the upper limits of an extreme event, this NRC study was a timely effort for engineers. The NRC (1994) committee report recommended that although there was no immediate need to drastically change current engineering practices for designing large water infrastructures, more research was recommended to develop numerical atmospheric models to understand the impact of extreme climate events and associated PMP estimation to changing boundary conditions.

The NRC (1994) report followed by the Abbs (1999) model-based study on PMPs ushered the engineering community into the 21st century with more frequent use of numerical models to understand an infrastructure's sensitivity to extreme events (e.g., Chen and Bradley 2006; Tan 2010; Ohara et al. 2011; Beauchamp et al. 2013). However, it is not yet clear how many of these model-based studies are used for improving resilience of water management infrastructure.

## Toward Greater Use of Numerical Models of Atmosphere

Before the use of computers (1960s) for complex modeling, the engineering community had to depend on procedures that were ad hoc and linear. However, such ad hoc procedures did not allow one to address the important question facing the engineering community of whether the engineering methods for storm management infrastructure planning and design would remain adequate to protect society from flooding hazards in the coming decades. For example, in the early 2010s the standard engineering practice

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for estimation of PMP involved a linear and regression-based forcing of atmospheric conditions associated with past extreme precipitation events (Rackhecha and Singh 2009). This approach was criticized as being insufficiently physical because it assumed a linear relationship between precipitation and water holding capacity of the atmosphere. This causes a discrepancy between conventional PMP estimates and what would be consistent using modern physically based climate and weather modeling methods. It may be acceptable to adopt such ad hoc approaches that lead to the overdesign of high-hazard infrastructure (Micovic et al. 2015) as long as the associated higher price is accounted for. Nevertheless, there currently is no reason for engineers to not take advantage of advanced computer technology that can integrate data on atmosphere science to compute complex numerical models that address various external changes facing water management.

In June 2014 the U.S. Army Corps of Engineers (USACE) produced an update to their Climate Adaptation policy as part of its Climate Resilience strategy (USACE 2014). This Climate Preparedness and Resilience Policy Statement states that "Mainstreaming climate change adaptation means that it will be considered at every step in the project life cycle for all USACE projects, both existing and planned . . . to reduce vulnerabilities and enhance the resilience of our water-resource infrastructure." To do so, USACE is developing with its partners and stakeholders practical, nationally consistent, legally justifiable, and cost-effective measures, both structural and nonstructural, to reduce vulnerabilities and improve the resilience of water related infrastructure affected by climate change and other global changes.

Articles in the November 2015 issue of the ASCE *Civil Engineering* magazine suggested that water managers are now paying attention to the growing body of work on the use of numerical models for PMP reassessment and for short-term (7–10 day) weather forecasts. Such models can reduce wastage of impounded water and plan for more water storage during periods of prolonged drought (ASCE 2015).

## Notable Approaches for Resilience Assessment from Other Disciplines

For infrastructure networks, Cavarallo et al. (2014) provided a methodology for the assessment of urban resilience to catastrophic events, such as a hurricane or a major drought. This approach aimed to bridge the gap between engineering and ecosystem considerations for designing resilient infrastructure. Cavarallo et al. (2014) integrated the social component to resilience and demonstrated its application to simulated earthquakes in the city of Acerra, Italy. This approach could be applied to the collective improvement of resilience of networked water management infrastructures (i.e., a series of dams along a river, or a large stormwater and water supply infrastructure of a city). Other work on resilience assessment of interdependent components for the design of networked infrastructure includes Reed et al. (2009).

Upadhay et al. (2014) provided insights regarding water infrastructure systems in Canada that this TC can leverage for U.S. infrastructure. Although the water management infrastructure is quite similar in design (with the exception of colder ambient conditions), the Canadian engineering profession rates their nation's infrastructure as "good but headed towards fair," unlike in the United States. Upadhay et al. (2014) used the example of stormwater infrastructure to examine current sustainability assessment methods. They reported that most methods of assessing infrastructure address functional aspects and resource-use reduction but do not consider long-term sustainability issues concerning maintaining resilience. To address this, in addition to climate, their resilience assessment included economic, health and safety, population growth, ecological and institutional factors. On the issue of climate, they claimed

> "Climate change science and modeling currently is not at a level of detail suitable for storm water management where knowledge of the intensity, duration, frequency of storms and their locations and timing is required. However the economic, health and environmental risks dictate a need to be proactive in the management of storm water."

Upadhay et al. (2014) further wrote, "These uncertainties require a process for continuously assessing the adapted measures, as well as assessing the physical facilities or infrastructures affected by these adaptations."

Micovic et al. (2015) reported a methodology for estimating the uncertainty in conventional estimates of PMP. To address such uncertainty and the general lack of consideration of sustainability in infrastructure resilience assessment, Upadhay et al. (2014) presented a protocol for extreme climate events that is relevant to this TC. This protocol is called the Public Infrastructure Engineering Vulnerability Committee (PIEVC). It is designed to "assess the vulnerability of buildings, roads and associated structures, storm water and wastewater systems, and water resources." The PIEVC proposes the following five steps:

1. Project definition;
2. Data gathering and sufficiency;
3. Risk assessment;
4. Engineering analysis; and
5. Conclusions and recommendations.

Upadhay et al. (2014) explained the PIEVC approach as follows:

> "In the project definition stage, the infrastructure to be assessed, time period of study, and required climate parameters (note: this is where the TC can recommend extreme weather related parameters such as PMP and PMF) are established. Next, relevant data are gathered and then in the risk assessment phase, the relationship between climate loads and the infrastructure capacity are determined. Vulnerability will exist if the load exceeds the capacity of the infrastructure. In the risk assessment stage, the following formula is applied: $R = P \times S$, where, $R$ is the risk, $P$ is the probability of extreme climate event, and $S$ is the severity of the infrastructure component response. Generally, the risk assessment process is undertaken in a workshop setting involving multiple experts, employing a number of assumptions, and using a consensus decision process. A risk matrix is developed and the vulnerability of the infrastructure is based upon the experience of the operators and managers. An engineering analysis is required where potential vulnerability exists and data quality is also undertaken. Medium risk items are evaluated, high-risk items move directly to recommendations, and low risk items are eliminated. Recommendations on remedial action, management action, no action or additional study requirements are made for the vulnerable infrastructure components."

In the United Kingdom, a similar approach for improving infrastructure resilience was promoted after the United Kingdom floods of 2007 and the cold snap of 2011–2012. Essentially, this approach recognizes the need for infrastructure resilience for business continuity. The methodology consists of a database of causal interactions which when used with a set process allows users to produce causal loop diagrams. These add value by identifying unanticipated systemic behavior, communicating risks, sharing knowledge, and

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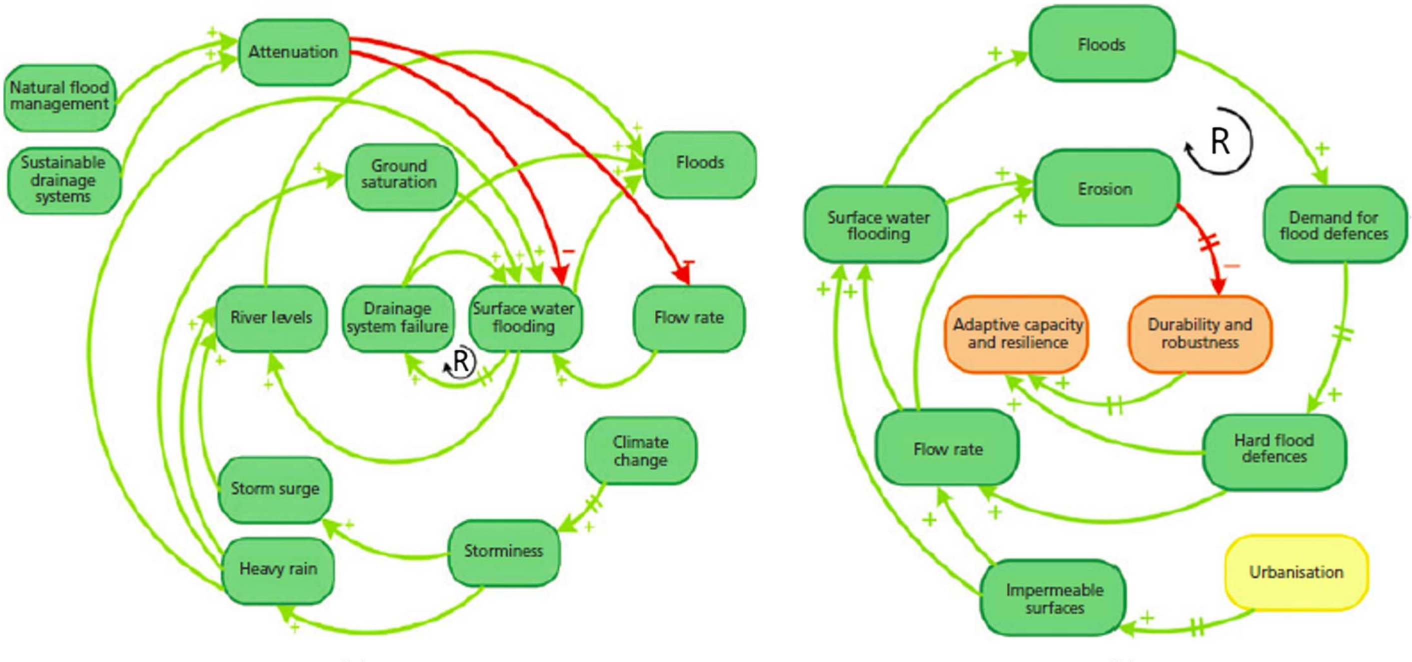

(a) (b)

**Fig. 1.** Causal loop diagram approach proposed by Montgomery et al. (2012) for infrastructure resilience improvement; the examples for the causal loop are for flooding impact on infrastructure (reprinted from Montgomery et al. 2012, with permission from ICE Publishing)

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identifying systemic intervention points that minimize negative consequences (Montgomery et al. 2012). The causal loop diagram proposed in this methodology is of relevance to this TC for improving infrastructure resilience for water management. In Fig. 1, two causal loop diagrams for flooding impact on infrastructure are directly reprinted. The first TC report (Hossain et al. 2015a) had a similar causal loop for the role of land–atmosphere feedbacks on extreme events, although at the time the TC was not aware of such insightful work across done in the United Kingdom by Montgomery et al. (2012).

## Conclusions

A review of literature revealed published methodologies for improving infrastructure resilience for water management, particularly large dams, for the ASCE TC on Infrastructure Impacts for Landscape-Driven Weather Change. This review revealed several new practices that are currently available for resilience assessment. These have already gained acceptance by civil engineers in geotechnical, transportation, and structural engineering. The review also revealed a long history within the ASCE (since the 1950s) of addressing infrastructure resilience issues caused by extreme climatic events. Lastly, the review identified four approaches used in allied disciplines within civil engineering that can be implemented for improving the resilience of large-scale water management infrastructure.

These four approaches for resilience assessment should be explored for their relevance and implementation by the water management community engaged in hydrologic and hydraulic engineering. In particular, the TC recommends greater use of numerical models to analyze past extremes and record their effectiveness in assessing current and future drivers of climate events for use in hydrologic design. If technologically sound, these model-based analyses can form the basis for improved design and resilience assessment of large-scale water management infrastructure.

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