Climate Change and Infrastructure Resilience

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Abstract

The energy, transportation and water infrastructure has evolved over time into inextricably interconnected systems. Traditionally, the engineering design practice of such systems have proceeded on the assumption of "climate stationarity" where the frequency and magnitude of weather patterns remain unchanged into the future. However, climate change introduces non-stationary stressors such sea level and temperature rise, and change in frequency and intensity of storms. Such stressors can take many forms and influence the system at varying spatial and temporal scales and require a holistic understanding.

Recent extreme events highlighted the importance of understanding interdependencies to strengthen infrastructure resilience and adaptive capacity in a changing climate. Classic examples of storms impacting the resilience of interconnected systems are hurricanes Sandy (2012), Harvey, and Irma (2017), which all caused disruptions to major water, transportation and energy systems in the United States that affected the functioning of other critical infrastructure (e.g., healthcare and telecommunications). In this context, resilience planning must not only account for the impacts of disruptive extreme weather events, but it must also account for the influence of long-term climate change induced stressors.

This work is focused on implementing state-of-the-art modeling techniques to better understand the impacts of natural (e.g., storms and floods) and anthropogenic (e.g., dam break) hazards, and gradual stressors (e.g., sea-level rise) on critical infrastructure.

This multidisciplinary research merges the fields of climate change, civil, water resources and coastal engineering, remote sensing and high-performance cloud computing to identify critical thresholds in aging infrastructure and cascade of failures in interconnected systems.

Introduction

Climate change is expected to alter the intensity, duration or frequency of climatic extremes over time, a concept termed non-stationarity (Cheng et al., 2014).

In general, engineering design metrics and assessment of risk are based on historical statistical analysis where hydrologic processes fluctuate in an unchanging envelope of variability. Such metrics play a critical role in guiding engineering design choices.

In inland and coastal urban areas, non-stationary processes are exacerbated by anthropogenic land-cover change such as deforestation, urban expansion and water diversions. In a changing climate, frequent multi-scale storm events can have implications on vulnerable and aging infrastructure that are contrasting to the implications from singular storm events.

Long-term sea-level rise is known as the main driver for accelerated flooding along the US coastline; however, changes in the joint distributions of storm surge and precipitation associated with climate variability and change also augment flood potential (Sweet, et al., 2014). Hurricane Irene (2011), for example, showed that when storm surge and heavy precipitation co-occur, the potential for flooding in low-lying coastal areas is often much greater than from either in isolation. Hurricane Irene brought extreme rainfall and accompanying flash floods in the States of New York, New Jersey, New Hampshire and Vermont with nearly 2,400 roads and 300 bridges destroyed or damaged from flooding (Saleh et al., 2016, 2018a 2018b). More recently, Tropical Storm Harvey (2017) brought more than 51 inches of rain in Texas which broken the record for the greatest amount of rain recorded from a single tropical storm or hurricane in the continental United States.

In the context of these factors, there is a pressing research need to develop strategies for engineers to (1) account for the effects of climate change in engineering design practice, where appropriate, and better understand the interactions to recognize the limits and opportunities of the current knowledge base upon which the decisions will be made; (2) justify when such changes are not warranted for a project of a particular type or scale. It is noted that there have been significant advancements in considering climate change information in coastal areas owing to the availability of sea level rise scenarios, analytical methods and tools. Yet, there is lack of knowledge in the inland and estuarine areas for compound events.

Use Case: A Focus on Dams and Storm Events

The United States have 90,580 dams[1] that provide important service and protection to communities and economy. The average age of dams is 56 years. Dams are classified based on their hazard potential (Table 1). As the population is growing and development continues, the number of high-hazard dams is increasing, with the number climbing to nearly 15,500 in 2016 (Example in Figure 1). Many existing dams were designed with relatively short hydrologic records so the use of longer accurate instrumental records, and future climate modeling is needed.

Failure by overtopping is one of the most common forms of catastrophic dam failure, and an increase in frequency and intensity of extreme rainfall may result in dam overtopping. In addition, as water levels rise from the increased inflows, the structural and hydraulic stresses that the weight of the additional water in the reservoir creates will likely exceed any levels previously experienced in a given dam.

Table 1 Dams Hazard level description[1]

Hazard Classification	Result of Failure or Misoperation
High Hazard	— Loss of life is probable. — Other economic or environmental loss possible, but not necessary for this classification.
Significant Hazard	— No probable loss of human life. — Could result in economic loss, environmental damage, and disruption of lifeline facilities, etc.
Low Hazard	— No probable loss of human life. — Few economic or environmental losses; losses are generally limited to the owner.

It is often the case that *man-made and natural disturbances* do not happen in isolation and their impacts can vary temporally and spatially. Such compound events are likely to have more important consequences, causing tipping points and major disturbances to critical infrastructure. To address this aspect, a predictive framework was developed to evaluate implications of man-made induced and natural disturbance scenarios such as future storm surge and intensive rainfall storms triggering dam overtopping or break. An attractive test bed located in a complex estuarine system (Figure 1) was selected to critically evaluate infrastructure resilience for two contrasting extreme flood events, hurricanes Irene (2011) and Sandy (2012). The two events emphasize the importance of detailed integrated modeling efforts that are subject to compound effects of coastal storm surge and riverine flooding.

1 ASCE's 2017 Infrastructure Report Card https://www.infrastructurereportcard.org/cat-item/dams/

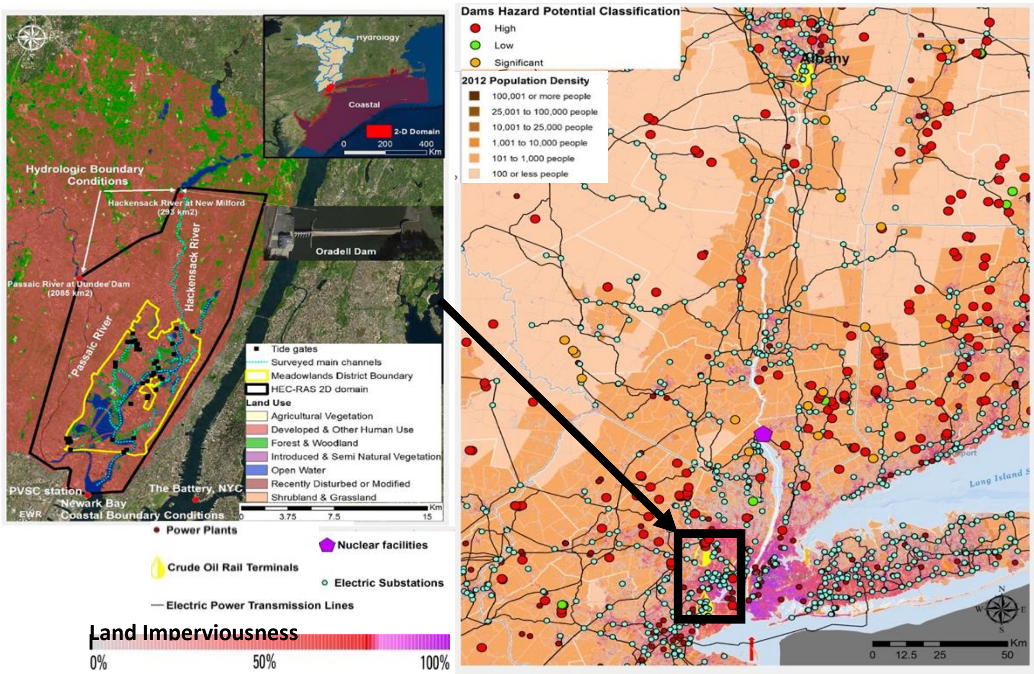

Figure 1. Test bed showing the interconnected system and multi-scale modeling components

The test bed captures long-term and short-term stressors: 1) a coastal environment subject to sea level rise; 2) a steep gradient in population density; 3) an infrastructure serving one of the largest metropolitan areas in the US; 4) highly urbanized area with valuable commercial and residential assets; 5) a history of environmental impacts, ranging from heatwaves, hurricanes to localized storms; and 6) a wealth of historic and real-time data and extensive monitoring facilities. The local scale area is bounded by two dams, the Passaic River at Dundee Dam, the Hackensack River at New Milford (downstream of Oradell Reservoir, built in 1923) and the tidal influence of Newark Bay from the south (Saleh et al., 2017).

To establish baseline inundation extents, the inland hydrodynamic component of the modeling framework was forced with the best available forcing data, represented by measured streamflow and ocean water levels (Figure 2). The extents simulated by the model for Hurricane Irene was a combination of storm surge and major hydrologic flooding. In contrast, Hurricane Sandy flooding was dominated by coastal storm surge that overtopped all existing berms and several tide gates in the area of study (Figure 2). The analysis for Hurricane Sandy suggest that the storm surge propagated 36.2 km inland along the Hackensack River up to the Oradell dam (Figure 1 & 2). Upon establishing baseline conditions, the framework was then forced with probabilistic and scenario-based sea level rise projections and change in rainfall to help stakeholders and practitioners understand the long-term risk in a changing climate.

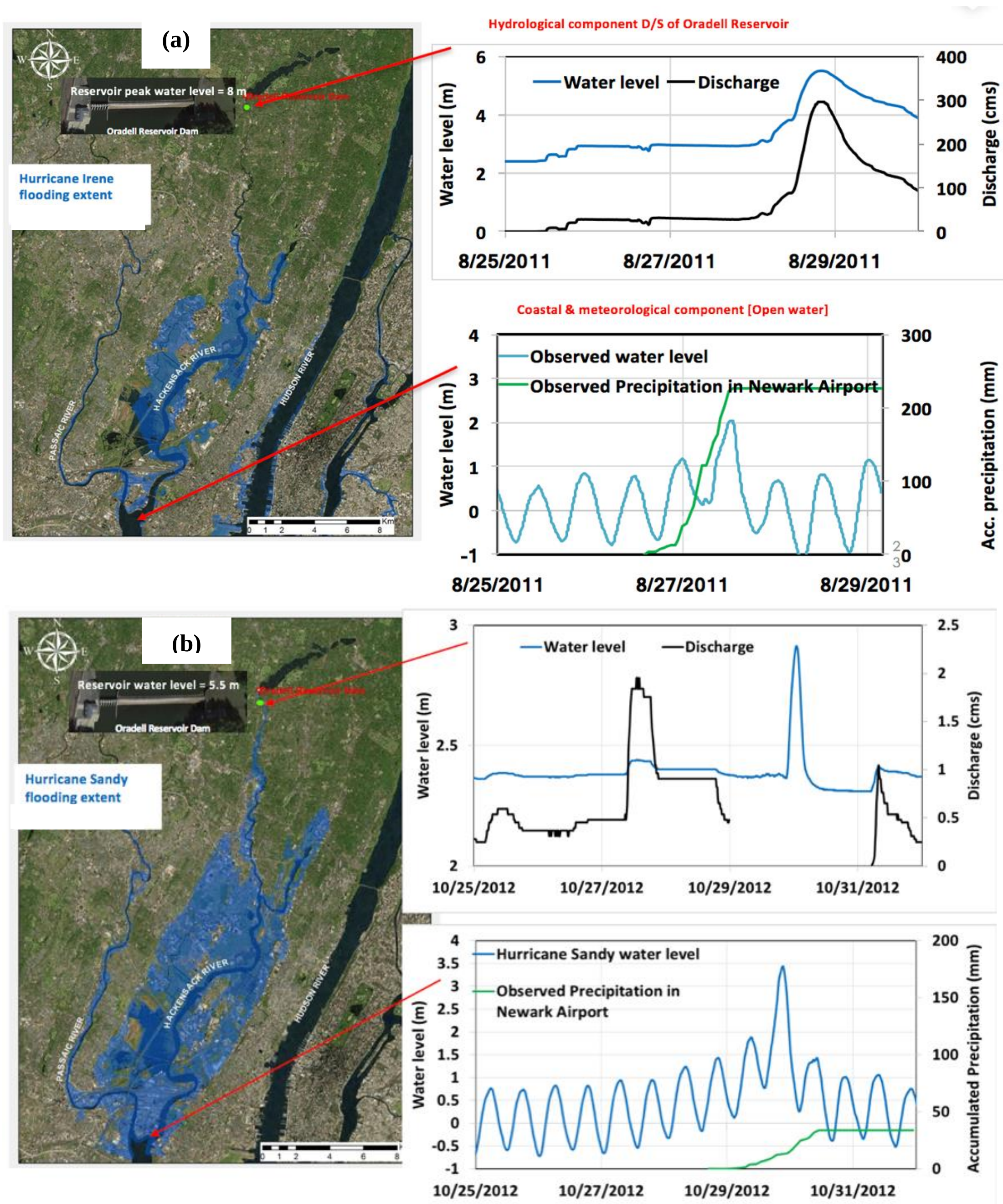

Figure 2. Flooding extent for the combined impact of riverine and tidal components during a) hurricane Irene and b) Sandy showing the observed accumulated precipitation and coastal water levels (including surge) at the Newark Bay.

Summary and Discussion

Intelligent modeling frameworks representing hydrosystem components spanning numerous temporal and spatial scales were integrated to provide telescopic capabilities for modeling coastal and inland flooding. The outputs provide important information to quantify integrated processes at decision-relevant scales and are essential to highlight significant vulnerabilities and mitigate the associated high-impact risks in critical infrastructure.

The framework can be used to quantify the impacts on the paired bilateral interfaces of energy-water from natural (e.g., storms and floods) and anthropogenic (e.g., dam break) shocks and explore the complex interactions with other gradual stressors (e.g., climate change and change in land use).

In perspective, coupling the system level models of the framework with regional scale climate change projections help identify the strong and weak linkages between the different components and non-linear behaviors and responses across scales. Stressors and constraints can take many forms and influence the system at varying spatial and temporal scales. These compound events can be from 1) two or more extreme events occurring simultaneously or successively (e.g., storm surge, hurricanes, Nor'easters, dam failures and precipitation-induced high river discharge) or 2) combinations of extreme events with underlying conditions that amplify the impact of the events (e.g., soil moisture, droughts and prolonged heat waves), or 3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined (e.g., wet soil, snow melt with temperature anomalies).

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