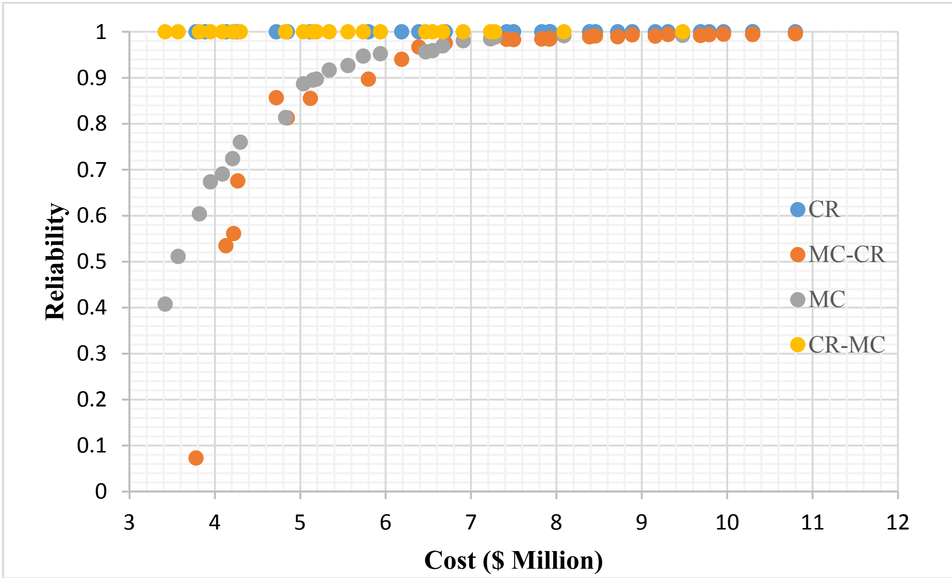

Figure 3. Comparison of the reliability measures

On the other hand, MC reliability values are based on the failure probabilities associated with the minimum cut-sets for each Pareto-optimal solution. Majority of the solutions were found to have only four minimum cut-sets. One limitation of the minimum cut-set method is the fact that it does not distinguish between failures of different magnitudes. Any shortcoming in meeting all the required demand at any of the nodes is considered a failure, and this makes it a very conservative approach for reliability assessment.

For comparative assessment of both the reliability approaches, MC values are calculated for all the Pareto-optimal CR solutions and vice versa. The MC values for CR solutions are represented as MC-CR and CR values for MC solutions are represented as CR-MC. The CR-MC and MC-CR plots are also included in Figure 3. It can be observed from Figure 3 that MC values are superior to MC-CR values at comparable costs. It can also be observed that it is difficult to compare CR values with CR-MC values as all of them are very close to 1.

CONCLUSIONS AND RECOMMENDATIONS

Water distribution systems are one of the critical infrastructures supporting communities and it is vital that they are continuously functioning. Given the myriad of possible threats, it is pertinent for water utility operators to continuously assess the reliability of their systems and take appropriate actions to enhance reliability and minimize risk. Two reliability approaches, namely contingency reliability and minimum cut-set approach, are comparatively assessed in this study by separately using them as part of multi-objective design optimization of water distribution systems. The contingency reliability approach produced very high reliability values for all the resulting solutions, whereas the minimum cut-set approach produced more evenly distributed reliability values. Previous studies have either not used pressure driven demand (PDD) analysis or used an iterative PDD approach that could be computationally intensive. This paper uses a computationally efficient non-iterative PDD analysis for evaluating WDS reliability using two established approaches. Minimum cut-set approach was found to have generally performed better than the contingency reliability approach. Both approaches were found to have certain limitations. A hybrid minimum cut-set approach in which a threshold demand-dissatisfaction that would distinguish concerning system failures from other failures may be more useful. Similarly, a modified contingency reliability approach that is suitable for all types of water distribution system configurations and sizes may be more useful. Relative merits of different reliability approaches identified in this study will support the optimal design and rehabilitation decision making for water distribution systems in a computationally efficient manner.

ACKNOWLEDGMENTS

The authors are thankful to King Saud University for supporting this research study through a student fellowship. This research was also partly supported by the National Science Foundation (NSF) under Grant No. 1638321. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the United States Government. The support of the NSF is greatly appreciated.

REFERENCES

Billinton, R. and Allan, R.N. "*Reliability Evaluation of Engineering Systems Concepts and Techniques"*. London: Pitman, 1983.

Ciaponi, C., Franchioli, L., & Papiri, S. (2011). "Simplified procedure for water distribution networks reliability assessment." *Journal of Water Resources Planning and Management*, *138*(4), 368-376.

Gargano, R., and Pianese, D. (2000). "Reliability as tool for hydraulic network planning." *J. Hydraul. Eng.,* 126(5), 354–364.

Goulter, I.C. and Coals, A.V., 1986. Quantitative approaches to reliability assessment in pipe networks. Journal of Transportation Engineering, 112(3), pp.287-301.

Khomsi, D., Walters, G. A., Thorley, A. R. D., and Ouazar, D. (1996)."Reliability Tester for water distribution networks." J. Computing in Civil Eng., 10(1), 10–19.

Ozger, Sukru Serkan, and L. W. Mays. "A semi-pressure-driven approach to reliability assessment of water distribution networks." PhD diss., Arizona State University, 2003.

Rossman, L.A. *EPANET – User's Manual.* Cincinnati, Ohio: United States Environmental Protection Agency (USEPA), 2000.

Sayyed, Mohd Abbas H. Abdy, Rajesh Gupta, and Tiku T. Tanyimboh. "Noniterative application of EPANET for pressure dependent modelling of water distribution systems." *Water resources management* 29.9 (2015): 3227-3242.

Su, Y.C., Mays, L.W. and Lansey, K.E. "Reliability-based Optimization Model for Water Distribution Systems." *ASCE J. Hydraulic Eng.,* 113, No. 12 (1987), 1539-1556.

Tanymboh, T. T., Tabesh, M., and Burrow, R. (2001). "Appraisal of source head methods for calculating reliability of water distribution networks." *J. Water Resour. Plann. Manage.,* 127(4), 206–213.

Synthesis of Water Infrastructure Adaptation Practices in U.S. Coastal Regions

Sreeganesh R. Yerri[1]; Kalyan R. Piratla[2]; Brandon E. Ross[3]; and Daniel M. Harrison[4]

[1]Graduate Research Assistant, Glenn Dept. of Civil Engineering, Clemson Univ., Clemson, SC 29634. E-mail: syerri@g.clemson.edu

[2]Assistant Professor, Glenn Dept. of Civil Engineering, Clemson Univ., Clemson, SC 29634. E-mail: kpiratl@clemson.edu

[3]Assistant Professor, Glenn Dept. of Civil Engineering, Clemson Univ., Clemson, SC 29634. E-mail: bross2@clemson.edu

[4]Professor, Dept. of Government, Criminology, and Sociology, Lander Univ., Greenwood, SC 29649. E-mail: dharrison@lander.edu

Abstract

One inevitable consequence of climate change is the rising sea level, which could adversely affect critical infrastructures in the coastal regions. Thirteen percent of the world population and 39% of the U.S. population resides in such coastal regions. Specifically, water resources and supporting water infrastructure in many coastal regions have become increasingly vulnerable to both quality and capacity issues. For example, nuisance-flooding events in low-lying coastal cities and salt-water intrusion into drinking water aquifers are becoming more frequent occurrences with rising sea levels. Several coastal states have already devised and implemented water infrastructure adaptation measures to effectively address the current and anticipated challenges of sea level rise. This paper presents the preliminary results of a comprehensive synthesis of water infrastructure adaptation practices in several coastal communities. A detailed review of policy documents published by various local, state and federal water infrastructure related agencies in the U.S. are reviewed to develop the database of water infrastructure adaptation strategies described in this paper.

Introduction

The earth's surface temperature has increased significantly since late 19th century. There is clear scientific evidence that the rising trend of the world's temperature will continue for at least a few more decades [6]. One inevitable consequence of global warming is raising sea level due to melting of glaciers and thermal expansion of oceans. Sea-level rise (SLR) can adversely affect critical infrastructure systems in coastal regions; 13% of the world and 39% of U.S. populations reside in these regions [1]. Several studies over the past decade have examined sea level rise and its consequences. A few of the crucial studies are summarized in this section.

Based on historic trends and recent modeling techniques, Lesley [3] investigated the range of sea level change that can be anticipated for the next 50 to 100 years. The work estimates the threshold at which current adaptation strategies will no longer be effective and identifying the critical weaknesses in current engineering and management efforts [3]. In another study, it is reported that accelerated SLR is bound to have costly effects on the mankind as more than 10% of the world's population lives in coastal regions that are at elevations lower than 10m above sea level. Gradual inundation, storm and tidal flooding, and saltwater intrusion are some of the impending threats to such regions [4].

Uncertainties in modeling have led to a range of sea level raise (SLR) predictions. For this century, predictions range from 0.18 to 5 m [9]. While government agencies in several regions across the world are being proactive in preparing to deal with the anticipated SLR impacts, there are certain political and societal challenges. Public is reported to be generally reluctant to adopt SLR adaptation measures unless they witness direct and dramatic SLR related events [9]. Furthermore, the large uncertainty in SLR projections exacerbates the public's willingness to adopt SLR adaptation measures [9]. For example, several residents in Charleston region of South Carolina were reportedly not very receptive of some of the SLR adaptation practices (e.g. buying back vulnerable properties) administered by the local agencies until they witnessed the 2015 South Carolina flooding event first hand. The water infrastructure stakeholders in Charleston region have shared their experiences of public acceptance with the authors as part of an ongoing research study.

Expansion of oceans due to the melting of glaciers and rising temperatures has resulted in a SLR of approximately 1.7mm/year over the last century and over 3.2 mm/year in the last few decades [10]. Accelerated SLR and increase in atmospheric temperatures, often described as the two most detrimental impacts of climate change, have devastating societal impacts that are already being realized, especially in the low-lying coastal regions of the southeastern United States. Such impacts include but are not limited to changes in precipitation cycles, increased storm intensity and flooding, increased coastal erosion, rising water tables, salt-water intrusion into freshwater aquifers, and septic system inundation. Aged, inadequate and outdated water infrastructures amplify the impacts of climate change. Understanding the effects of these issues is crucial for instilling hazard resilience. Several critical climate change impacts on coastal water infrastructures are identified in Table 1.

Table 1. Climate change impacts on coastal water infrastructures

Drinking Water	Wastewater	Stormwater
• Intrusion of salt water into freshwater aquifers • Evapo-transpiration of surface water • Freshwater shortages	• Inundation of low-lying pumping stations • Inflow & infiltration into deteriorated pipelines • Backflow risk • Increased demand for wastewater treatment capacity • Effluent disposal problems	• Inadequate pumping and storage capacity • Backflow during tidal flooding • Accelerated deterioration of infrastructure due to repeated exposure to salt water

This paper addresses the following question: What is currently being done to address SLR in coastal communities? The value proposition of this paper is that it presents a comprehensive synthesis of SLR adaptation measures in a single document. Coastal water agencies currently implement several adaptation measures to counter SLR impacts on their communities. These measures are wide ranging and there is currently a lack of a comprehensive database of best adaptation practices. The synthesis presented in this paper is based on the review of 29 reports and other relevant documents published by public agencies operating in various coastal states. Furthermore, this paper highlights the differences in some of the measures implemented across various states. This paper would serve as a good reference for coastal communities interested in planning SLR adaptation. Specific examples of adaptation measures are provided. This paper represents the first phase of a larger project focused on comparatively evaluating the synthesized best adaptation practices and developing recommendations for coastal water agencies in South Carolina for better planning of addressing the anticipated SLR impacts.

Study Methodology

The methodology used in this study entails aggregating and comparatively analyzing the state-of-practice related to coastal water infrastructure adaptation. SLR related adaptation measures that are currently being implemented in several regions across the United States are synthesized. Specifically, published documents by various state and federal agencies were reviewed with an objective of identifying and categorizing the adaptation measures. Policies/strategies implemented and/or described by agencies in the following states have been synthesized: Connecticut [11] [12] [13], Virginia [14], Delaware [15] [16], California [8], Maryland [17], North Carolina [5], New York [18] [19] [20], New Jersey [21] [22], Florida [23] [24] [25], Massachusetts [26] [7] [27] [28], Washington [6] [29], New Hampshire [30] [31], Maine [32] [33] [34], and South Carolina [35] [36]. Strategies are classified under four categories: (a) policies; (b) physical modification; (c) awareness; and (d) modeling. These categories are described in the sections below and are listed along with the strategies in Tables 2 and 3.

Policies:

Policymaking plays a major role in regulating development, preparedness and risk sharing in coastal communities that are vulnerable to SLR impacts. Regulatory policies should focus on preventing further loss to existing development, while at the same time planning for the future development of communities and infrastructures that would become vulnerable to rising SLR impacts. Various policies have already been implemented by local and state agencies. Several policies related to procurement of funding – i.e., seeking federal funding and developing other types of funding mechanisms – were found in the reviewed documents of states such as Washington, Florida, New Jersey and South Carolina. Several states also have policies focused on planning and evacuation, preparing flood hazard mitigation plans, requirement of elevating evacuation routes, and promotion of best evacuation routes. Other focus areas of currently implemented policies include identification and restriction of development in vulnerable areas, mandating insurance coverage, impact assessment on health, transportation and other infrastructure sectors. Several policies also focused on coordination among public agencies for knowledge sharing, data collection on sea level rise and shoreline mitigation, and training programs for working personal regarding climate adaptation. Table 2 lists various popular policies adopted across various states.

Physical Modification:

Strategies related to the physical modification of infrastructure could cease/impede the sea level rise impacts. A detailed analysis is necessary before these strategies could be implemented as significant capital investment is required. Across several regions, data is being collected from current SLR related events for projecting future impact assessment and to subsequently determine optimal infrastructure enhancement schemes. Procurement of funding is also crucial while planning any infrastructure enhancement. Physical infrastructure modification could involve rehabilitation or expansion of existing structures, as well as building new facilities.

Increasing storage and pumping capacity of the drainage infrastructure is a popular physical modification strategy followed in several states such as New York, Virginia, South Carolina, and Delaware. Physical structures like sea walls, rolling easements are considered helpful in diminishing the impacts and are practiced in states such as Maine. Other physical modifications include identifying and raising elevations of primary streets that are expected to be impacted (e.g. inundated) by SLR impacts in the future, adopting porous pavements, and building green roofs.

Physical modifications need not be in the form of permanent structures. The Port Authority of New York and New Jersey has recommended the use of modular barriers that can be temporarily installed to mitigate imminent flooding hazards. Benefits of the temporary barriers include reduced cost (relative to permanent structures), ease of installation, and the ability to respond to incremental SLR changes. One drawback of this system is that it requires active and continuous monitoring of impending risk hazards so that barriers can be effectively deployed. [16]

Awareness:

Various strategies are developed to create awareness among the public and other stakeholders on climate change and sea level rise impacts on the society and environment. It is important to educate the public on primary causes of sea level rise, their impacts, and communicate what adaptation measures are being implemented and how the public can be involved to make the adaptation more efficient. Different states do it in different ways. In Maryland, outreach groups are formed for campaigning, organizing workshops and presentations to public to create awareness on coastal community adaptation. In New York, direct interaction strategies are used for awareness by organizing field trips, issuing forms and adaptation measures manual to public. Indirect interaction strategies are also developed by incorporating the awareness information/tools in the education system – followed in the state of Connecticut. Awareness through establishing alerts systems and signage at vulnerable areas are also considered to be strategies in some states.

Modeling:

Modeling deals with better understanding of the hazards and the resulting impacts with the goal of accurately predicting future impacts for appropriate planning and preparedness. Use of monitoring equipment to record and analyze the change in sea level rise, data collection through tidal gauges, flood tracking locations, sea level trends, and erosion patterns are widely used in Florida, New Jersey and New York. Maps to identify the vulnerability of water infrastructure to storm events and sea level rise, and forecasting wetland trends, rainfall patterns are some modeling strategies followed in states such as Washington, and New Jersey.

In some cases, strategies fall into two or more of the categories. For example, the city of Coral Gables, FL has created a Light Detection and Ranging (LiDAR)-based map of elevations throughout the city [37]; the map is aimed at creating awareness among the city residents. Data represented on the map has also been used for modeling and for informing policy decisions and physical modifications [38].

In addition to official government-driven adaptation measures, market forces are also reacting to SLR. Market forces are beyond the scope of this paper, however, one example is offered. In Miami, FL, real estate values in higher elevation areas away from the coast are increasing in value; this increase is attributed in part to growing desire to own property that is less susceptible to the effects of SLR [2].

Table 2. SLR Adaptation Policies Formulated or Practiced across Coastal Regions in the U.S.

Strategies (policy category)	States
Identify vulnerable areas	CT, VA, CA, DE, MD, NC, NY, NJ, FL, MA, WA, NH, ME, SC
Develop adaptation funding mechanisms	CT, VA, DE, NY, NJ, FL, MA, WA, NH, ME, SC
Restrict development in vulnerable areas	CT, DE, CA, MD, NC, NY, NJ, FL, MA, WA, ME, SC
Incentivize owners to adopt adaptation measures	CT, VA, DE, CA, MD, NY, NJ, FL, MA, WA, NH, SC
Buy out properties in vulnerable areas	DE, NC, NY, MA, WA, NH, SC
Improve coordination among public agencies	CT, NJ, FL, MA, WA, SC
Mandate collection of crucial data	CT, NY, FL, MD, MA, WA, NH, SC
Formulate and test evacuation policies	CT, DE, NJ, FL, WA, NH, SC
Train workforce in adaptation measures	DE, NY, WA, NH
Mandate infrastructure maintenance	VA, MD, NC, MA, WA, ME, SC
Mandate risk assessment to support policy making	CT, VA, DE, CA, MD, NC, NY, NJ, FL, MA, WA, NH, SC
Mandate planning for climate change impacts	CT, VA, DE, CA, MD, NC, NY, NJ, FL, WA, NH, ME, SC

Table 3. Other Categories of SLR Adaptation Strategies Formulated or Practiced across the Coastal Regions in the U.S.

Physical Modification	Increase storage and pumping capacity of the drainage infrastructure	SC, NC, FL, MA
	Build physical barriers such as sea walls to minimize impacts of tidal events	VA, NY, FL, WA, NH, ME, SC
	Raise elevations of the built environment such as roadways	NC, MA, WA, ME, SC
	Design and build floatable critical properties	MA, NC
	Relocate facilities/people located in critically vulnerable regions	CT, NC, FL, MA, WA
	Rehabilitate infrastructure proactively	MD, NC, SC, MA
	Adopt green infrastructure planning	VA, DE, NY, FL, MA, WA, NH
Awareness	Form public outreach groups	VA, NY, NJ, FL, MA, WA, NH, SC
	Enable direct public interactions	CT, NY, FL, SC, MD, NC
	Enable indirect public interactions	NC, NY, NJ, FL, SC
	Develop efficient warning systems	FL, NC, NY
Modeling	Map vulnerable areas and critical facilities	DE, NC, NY, FL, MA, WA, NH, ME
	Collect critical data for monitoring purposes	CT, VA, NY, NJ, FL, MA, WA, NH, ME, SC
	Forecast future impacts of sea level rise	CT, DE, MD, NY, NJ, FL, MA, WA, NH
	Revise codes/policies based on model predictions	DE, NC, NY, MA, WA, NH, ME

While some of the strategies listed in Tables 2 and 3 are effective in addressing all kinds of SLR impacts, some are aimed at specific hazards. Strategies such as "forming public outreach groups" would support community adaptation to all kinds of SLR impacts. Other strategies such as "building physical barriers (e.g. seawalls)" would minimize the impacts of tidal flooding and coastal erosion. Similarly, strategies such as "increasing storage and pumping capacity of the drainage infrastructure" will minimize the risk of inundation to roads and septic systems in vulnerable areas. Strategies such as "relocating facilities/people located in critically vulnerable regions," "restricting development in vulnerable areas," and "buying out properties in vulnerable areas" are preventative in nature. Some other strategies are aimed at enhancing the resilience of physical structures to be able to better resist and sustain SLR impacts. "Raising elevations of the built environment such as roadways" and "designing and building floatable critical properties" are some of the resilience enhancing strategies against flooding hazard. Furthermore, some strategies such as "revising codes/policies based on model predictions of future SLR impacts" are aimed at adjusting the current adaptation practices considering the anticipated future SLR impacts.

Widely Used Strategies: Variation across the States

It can be seen from Table 2 that some of the adaptation strategies are commonly used across several states and therefore they are likely effective. Differences in their specific uses are however noticed across the states. An eminent strategy from each category is assessed based on how its specific use varied across the states, as shown in Tables 4, 5, 6 and 7. These distinctions in strategies are possibly due to the variation in socio-economic, SLR vulnerability, land use, and community support aspects across the states.