Available online at www.CivileJournal.org

Civil Engineering Journal

Vol. 6, No. 7, July, 2020

Review Article

A Systematic Review of Civil and Environmental Infrastructures for Coastal Adaptation to Sea Level Rise

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Received 30 March 2020; Accepted 08 June 2020

Abstract

Rising levels of seas and oceans due to global warming could drastically affect the daily lives of residents in coastal belts and lowland areas. Many of the most heavily populated regions in the world have been developed on the shorelines. Sea-level rise could directly affect the serviceability of urban structures and infrastructures of coastal regions; effects may include intrusion of salt water into drinking water resources, submergence of roads and railways, flowing of seawater into wastewater networks, and exacerbating land subsidence. These reasons have urged climate-change and infrastructure resilience researchers to focus on methods for prediction and prevention of SLR effects on urbanization systems. Most of the studies have concentrated on environmental aspects or modeling of flooding, however, there is a lack of research on behavior of urban lifelines for long-term planning. Hence, the resilience of coastal cities has become of more interest in recent years. This paper presents a meta- analysis and review of existing literatures on the impacts of SLR on civil infrastructure. We categorize these impacts based on different types of infrastructures (e.g. water, transportation, energy) and regions. The review provides i) an intensive coverage of the existing literature on adaptations ii) an exploration of current gaps and challenges in civil infrastructures in different regions of the world and iii) the engineering perspective of SLR besides managing directions to be useful for engineers, advisory committees, policy makers, and scholars for future studies.

Keywords: Sea Level Rise; Coastal Communities; Infrastructure; Resilience.

1. Introduction

Global warming has three dominant effects on coastal systems: increased temperatures, increased height of water levels, and increased acidity of water ecosystems. Coastal systems are lowland areas on the coasts of seas and oceans with two distinctions: human systems and natural systems. Sea Level Rise (SLR) generally causes submergence of lowland areas, coastal flooding, erosion of coasts, and intrusion of saltwater into drinking water [1]. Methods developed for preventing the destructive effects of SLR on the coastal regions are mitigation and adaptation. Mitigation focuses on reducing greenhouse gas emissions. Adaptation methods focus on the improvement of coastal systems to reduce the impact of SLR, such as protective structures, modification and elevation of infrastructures, and

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http://dx.doi.org/10.28991/cej-2020-03091555

retreat. Chronic SLR, aging rate, and increasing service demand in coastal communities will strain urban lifeline systems. Any disruption to urban lifeline serviceability can cause major difficulties to peoples' everyday activities and could have adverse economic impacts [2]. This review discusses the effects of SLR on coastal regions of the world and coastal infrastructures (including water, transportation systems, and energy supplement systems).

SLR could have severe consequences and cause mass evacuations in lowland coastal regions. The highest rates of urbanization in coastal regions are in China and Southwest Asia. In contrast, Europe, North America, and Oceania have the lowest rates of urbanization in coastal regions. Moreover, SLR is threatening countries with long coastlines such as Bangladesh and countries comprised of many islands, such as Indonesia and the Philippines [3]. Neumann et al. [4] estimated the population of lowland coastal zones of the world for years 2030 and 2060 based on the population estimation done for the year 2000. They estimated the increase in population size of lowland coasts based on four different scenarios of SLR and socio-economic conditions. The research indicated that the most densely populated coasts of the world are in Asia and will continue to be the most populated in the future. However, the study predicted that coasts of Africa, such as the coasts of Egypt and Nigeria, will have the highest rate of increase in population. According to population data, governments should consider flooding vulnerabilities and resilience of coastal infrastructures to protect coastal populations. Figure1 shows the predicted distribution of the coastal zone population in the world for 2030 and 2060 based on the four scenarios.

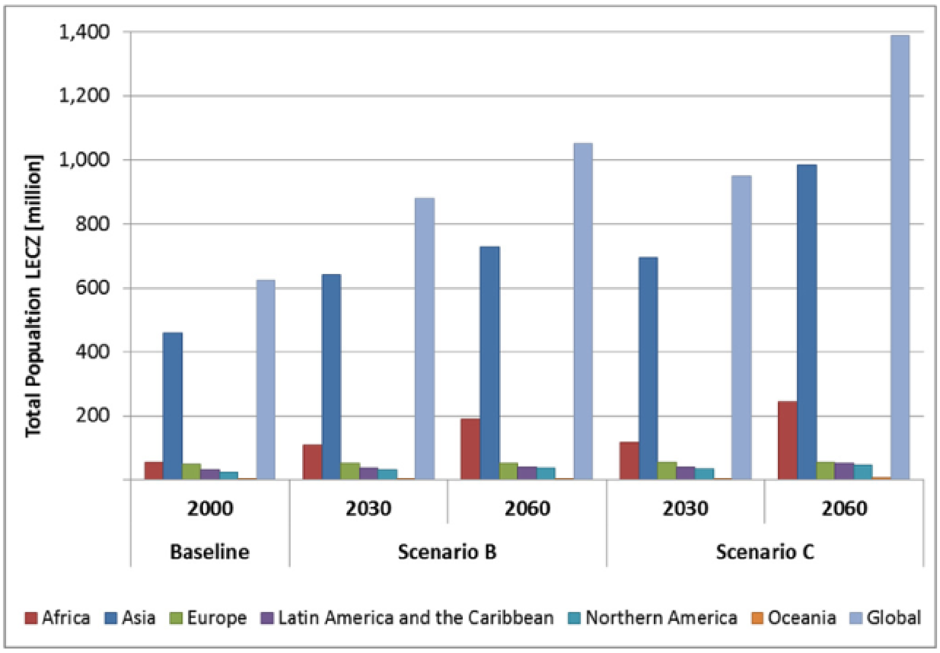


Figure 1. Prediction of distribution of peoples in coastal regions in the world from 2030 to 2060 [4]

The rest of this paper is structured as follows: Section 2 provides a brief review of the methodology used to prepare this article. Articles reviewed and their main objectives are summarized in Table 2.

Section 3 discusses the impacts and adaptations of SLR on different civil infrastructures in separate sub-sections. Important lessons from each region were determined and adaptations were assessed. Table 3 lists more reviewed case studies from around the world. Finally, Section 4 provides concluding remarks and direction for future research.

2. Methodology

In this article, more than 500 scholarly journals, conference papers, local and international technical reports have been collected, reviewed, selected, coded, sorted, compiled, and analysed to investigate various dimensions of emerging SLR concerns in coastal areas. Since this topic is an interdisciplinary concept, an engineering perspective along with other perspectives (e.g. environmental, financial, urban planning and development) impart better understanding of the context and adaptations. To conduct an organized search and maximize the efficiency, we implement a framework to cover the most related manuscripts and literatures. Figure 2 shows a framework of different steps to this end. Tables 2 and 3 report the distribution of the domain and years of publication. This review includes papers published from 1999 to 2019 with more focus on recent papers.

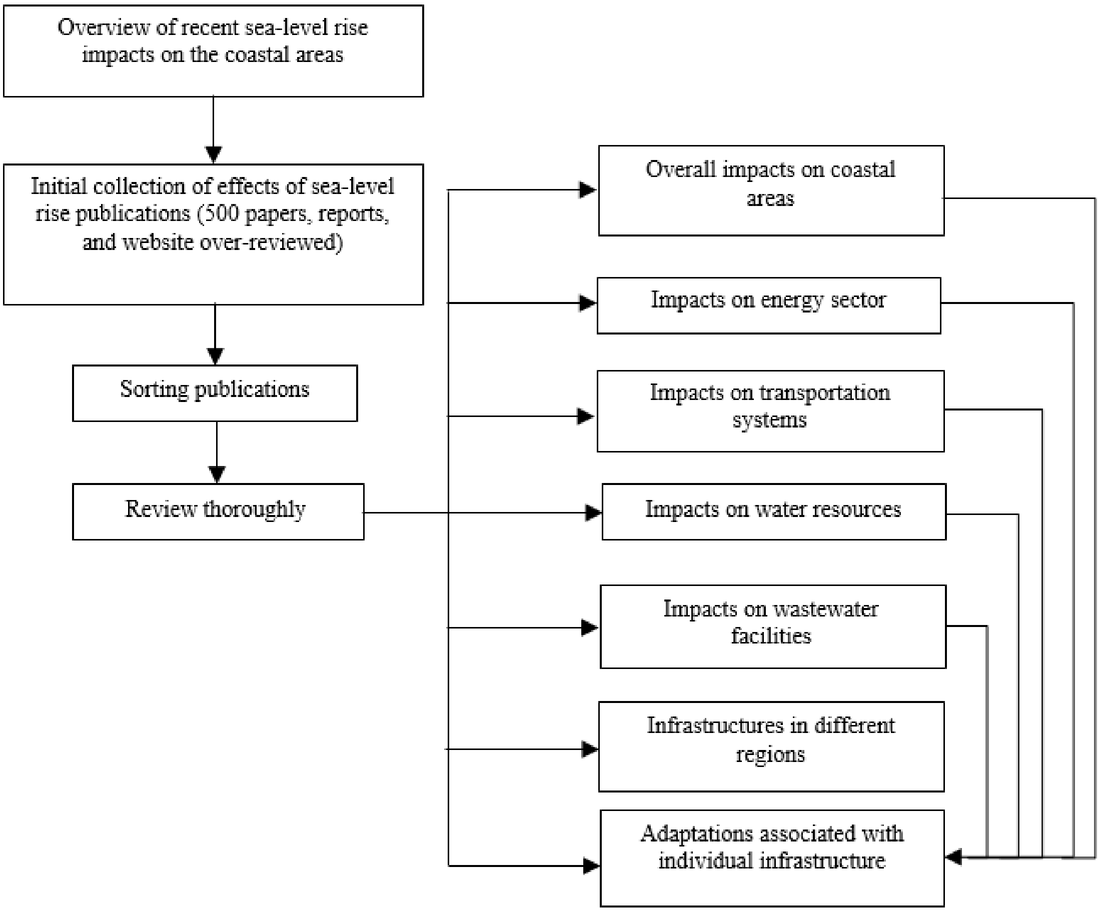


Figure 2. Flowchart of the literature screening methodology used in this review

Since social welfare and viability are integrated with civil infrastructure systems, any damage to lifelines could cause disruption to residential daily life. Hence, assessment and understanding of reactions and consequences of possible SLR phenomena is crucial and has drawn significant attention in recent years, specifically for rising sea level as a low to mid-probability and high-consequence disruptive event. Hence, this paper would be useful for policymakers, authorities, and scholars around the world. The main objective of this article is to evaluate the existing literature and case studies to expand the knowledge of engineers, scholars, and authorities. The following is a list of reviewed articles:

Table 1. List of reviewed manuscripts, year, and their domains

No	Literature	Aim
1	Abdoulhalik A and Ashraf A (2018) Transience of Seawater Intrusion and Retreat in Response to Incremental Water-Level Variations. Hydrological Processes 32(17):2721–33.	This paper estimates the rate of salty water intrusion in freshwater.
2	Abel N, Russell G, Ben H, Anne L, Langridge J, Ryan A, and Heyenga S (2011) Sea Level Rise, Coastal Development and Planned Retreat: Analytical Framework, Governance Principles and an Australian Case Study. Environmental Science and Policy 14(3):279–88.	This paper proposed some retreat principles for Queensland, such as dividing authority and resources between levels of government and establishing rules and incentives that provide feedback systems.
3	Abozaid (2008) Using Porous Seawalls to Protect the Coasts against Sea Level Rise Due to Climatic Changes. Msc Thesies, Zagazig University.	This paper suggested a novel seawall to reduce stone usage in the seawall construction using a combination of steel sheets and stone.
4	Allen T, Crawford T, Montz B, Whitehead J, Lovelace S, Hanks A, Christensen A, and Kearney G. (2018) Linking Water Infrastructure , Public Health , and Sea Level Rise : Integrated Assessment of Flood Resilience in Coastal Cities.	This paper aims to elucidate the effect of water and wastewater vulnerabilities on public health infrastructures.
5	Awang, N. A., M. R. Abdul Hamid, F. A. Mohd, A. H. Abd Razak, N. A. Abd Rahim, R. A. Begum, O. A. Karim, and K. N. Abdul Maulud. (2018) Assessment of Coastal Inundation of Low Lying Areas Due to Sea Level Rise. IOP Conference Series: Earth and Environmental Science 169:012046.	They studied the inundation of the Pahang coast of Malaysia under two sea-level rise scenarios.
6	Ayyub B Haralamb G and Qureshi N (2011) Prediction and Impact of Sea Level Rise on Properties and Infrastructure of Washington, DC. (4).	They proposed a linear model of GIS for predicting the effects of sea-level rise on the infrastructures of coasts of Washington DC.

7	Brown S, Hanson S, and Nicholls J. (2014) Implications of Sea-Level Rise and Extreme Events around Europe: A Review of Coastal Energy Infrastructure. Climatic Change 122(1–2):81–95.	They studied the effects of sea-level rise on the energy infrastructures of Europe with results stipulating that the energy facilities of the north-west of Europe are at risk.
8	Buzzanga, A. (2017) Precipitation and Sea Level Rise Impacts on Groundwater Levels in Virginia Beach , Virginia.	This paper investigated the effects of sea-level rise on the underground water flow on southeast Virginia coasts.
9	Carlson C, Gretchen G, and Kristina D Stormy Seas , Rising Risks : Assessing Undisclosed Risk from Sea Level Rise and Storm Surge at Coastal US Oil Refi Neries. 295–308.	This paper studied the effects of sea-level rise on the oil-refining system of U.S. coastal areas, concluding the systems are at risk and retreat rules should be more strictly followed.
10	Chun A, Changmook L, Daeha K, and Sung Kim J. (2018) Assessing Impacts of Climate Change and Sea-Level Rise on Seawater Intrusion in a Coastal Aquifer. Water (Switzerland) 10(4):1–11.	They considered the effects of freshwater recharge rate on the intrusion of salty water into underground water by finite elements and finite differences methods.
11	Cooper J, Andrew G and Orrin H (2004) Sea-Level Rise and Shoreline Retreat: Time to Abandon the Bruun Rule. Global and Planetary Change 43(3–4):157–71.	They focused on the limitation of the application of Brunn Rule for prediction of coastal retreat under sea-level rise conditions.
12	Dawson D, Shaw J, and Gehrels W (2016) Sea-Level Rise Impacts on Transport Infrastructure : The Notorious Case of the Coastal Railway Line at Dawlish , England. 51(February 2014):97–109.	They used a semi-empirical model to define the effects of sea-level rise on the rail system of England.
13	Dismukes D and Siddhartha N. (2018) Sea-Level Rise and Coastal Inundation: A Case Study of the Gulf Coast Energy Infrastructure. Natural Resources 09(04):150–74.	This paper analyzes the effects of sea-level rise on the energy systems of U.S. coasts, concluding that gas transmission systems are more at risk than other systems.
15	Dissanayake D, Ranasinghe R., and Roelvink J. (2012) The Morphological Response of Large Tidal Inlet/Basin Systems to Relative Sea Level Rise. Climatic Change 113(2):253–76.	They studied the response of a tidal region of Netherland coasts to sea-level rise.
16	Doughty L, Kyle C, Richard F, and Eric D (2018) Evaluating Regional Resiliency of Coastal Wetlands to Sea Level Rise through Hypsometry - Based Modeling. 1–15.	This paper proposed a rule-based model to study the effects of sea-level rise and dynamic effects of the accumulation of water in the mouth of coves. The coastline of California was selected as a case study.
17	Ehsan S, Rawshan A, Nor G, Khairul N, Abdul M (2019) Current and Potential Impacts of Sea Level Rise in the Coastal Areas of Malaysia. IOP Conference Series: Earth and Environmental Science 228(1).	This paper investigated the erosion and flooding effects on the coasts of Malaysia.
18	Fletcher, Charles H., Patrick L. Barnard, Curt D. Storlazzi, Li Erikson, Sean Vitousek, and Neil Frazer. (2017) Doubling of Coastal Flooding Frequency within Decades Due to Sea-Level Rise. Scientific Reports 7(1):1–9.	This paper details the effect of salinization of freshwater due to the inundation and intrusion of saltwater in Sweden.
19	Gesch, Dean B (2009) Analysis of Lidar Elevation Data for Improved Identification and Delineation of Lands Vulnerable to Sea-Level Rise. Journal of Coastal Research 10053:49–58.	These academics studied the effects of sea-level rise on the inundation of coastal zones of North Carolina with lidar maps.
20	Griffiths, James Andrew, Fang Fang Zhu, Faith Ka Shun Chan, and David Laurence Higgitt. (2018) Modeling the Impact of Sea-Level Rise on Urban Flood Probability in SE China. Geoscience Frontiers.	This paper investigated the effects of sea-level rise due to storm surge in Southeastern China. They studied the performance of the drainage channel with sea-level rise.
21	Hill, Kristina. (2015) Coastal Infrastructure : A Typology for the next Century of Adaptation to Sea-Level Rise.	This paper categorized coastal infrastructures for sea-level rise risk.
22	Hummel, Michelle A., Matthew S. Berry, and Mark T. Stacey. (2018). Sea Level Rise Impacts on Wastewater Treatment Systems Along the U.S. Coasts. Earth's Future 6(4):622–33.	They studied the effect of marine and groundwater inundation on the wastewater infrastructures of coastal regions.
23	Jenkins, Lisa Martine, Robert Alvarez, and Sarah Marie Jordaan (2019) Unmanaged Climate Risks to Spent Fuel from U. S . Nuclear Power Plants : The Case of Sea-Level Rise. Energy Policy.	This paper concentrates on the impacts of sea-level rise on nuclear plants in U.S. coastal regions.
24	Johnston, A, Slovinsky P and Yates K (2014) Assessing the Vulnerability of Coastal Infrastructure to Sea Level Rise Using Multi-Criteria Analysis in Scarborough, Maine (USA). Ocean and Coastal Management 95:176–88.	They investigated the impacts of sea-level rise on infrastructures in the coastal regions based on criteria such as economy, society, etc.
25	Johnston A, Slovinsky P and Yates K (2014) "Ocean & Coastal Management Assessing the Vulnerability of Coastal Infrastructure to Sea Level Rise Using Multi-Criteria Analysis in Scarborough , Maine (USA)." Ocean and Coastal Management 95:176–88.	They proposed a method to define the vulnerability of infrastructures for flooding conditions in U.S. coastal regions.
26	Joyce J, Ni-bin C, Rahim H, Thomas R, and Sanaz I. (2017) Environmental Modelling & Software Developing a Multi-Scale Modeling System for Resilience Assessment of Green-Grey Drainage Infrastructures under Climate Change and Sea Level Rise Impact. Environmental Modelling and Software 90:1–26.	This paper studied the relationship of SLR and resilience of the coastal water drainage system using a multi-scale modeling analysis for the Cross Bayou Canal of Florida.
27	Klein, Richard J. T., Robert J. Nicholls, Sachooda Ragoonaden, Michele Capobianco, James Aston, Earle N. Buckley, Richard J. T. Kleint, Robert J. Nichollst, James Astontt, and Earle N. Buckley (2001) Technological Options for Adaptation to Climate Change in Coastal Zones. Journal of Coastal Research Journal of Coastal Research 17(3):531–43.	This paper categorized the adaptation strategies for coastal management: protection, accommodation, and retreat.
28	Koetse, Mark J and Piet Rietveld (2009a & b) The Impact of Climate Change and Weather on Transport: An Overview of Empirical Findings. Transportation Research Part D 14(3):205–21.	The academics recommended that transportation infrastructures need more attention to the impacts of sea-level rise.

29	Lee, Yumi (2014) Coastal Planning Strategies for Adaptation to Sea Level Rise: A Case Study of Mokpo, Korea. Journal of Building Construction and Planning Research 02(01):74–81.	This paper recommends planning strategies for urban development resilience to sea-level rise of Mokpo, a city in South Korea.
30	Mimura, Nobuo. (1999) Vulnerability of Island Countries in the South Pacific to Sea Level Rise and Climate Change. Climate Research 12(2-3 SPEC. ISS. 6):137–43.	This paper emphasizes the vulnerabilities to rising sea-level for lowland island countries of the South Pacific
31	Moore, Eli, Pablo Herrera, Peter H. Gleick, Heather Cooley, and Matthew Heberger. (2011) Potential Impacts of Increased Coastal Flooding in California Due to Sea-Level Rise. Climatic Change 109(S1):229–49.	This paper investigated the erosion and flooding risks due to sea-level rise effects such as storms and tsunamis on the coastline of California.
32	Neumann, Barbara, Athanasios T. Vafeidis, Juliane Zimmermann, and Robert J. Nicholls (2015) Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment. PLoS ONE 10(3).	They estimated the exposure of coastal zone population to sea-level rise and flooding according to different scenarios.
33	Neumann, James E., Kerry A. Emanuel, Sai Ravela, Lindsay C. Ludwig, and Caroleen Verly (2015) Risks of Coastal Storm Surge and the Effect of Sea Level Rise in the Red River Delta, Vietnam. Sustainability (Switzerland) 7(6):6553–72.	They studied the effects of sea-level rise on the Red River Delta in Vietnam under storm and flooding conditions.
34	Pernetta, John C. (2002) Impacts of Climate Change and Sea-Level Rise on Small Island States. Global Environmental Change 2(1):19–31.	This paper highlighted the role of greenhouse gas production by industrial governments on the inundation of other lowland island countries.
35	Pinto, Pedro J., G. Mathias Kondolf, and Pun Lok Raymond Wong. (2018) Adapting to Sea Level Rise: Emerging Governance Issues in the San Francisco Bay Region. Environmental Science and Policy 90(August):28–37.	They discuss obstacles and strategies for adaptation in San Francisco Bay coasts.
36	Refaat, Mervat M. and Yasser Eldeberky (2016) Assessment of Coastal Inundation Due to Sea-Level Rise along the Mediterranean Coast of Egypt. Marine Geodesy 39(3–4):290–304.	This paper aims to define the impact of sea-level rise on the agriculture of the Nile Delta in Egypt due to inundation.
37	Rosenzweig, Cynthia, William D. Solecki, Reginald Blake, Malcolm Bowman, Craig Faris, Vivien Gornitz, Radley Horton, Klaus Jacob, Alice LeBlanc, Robin Leichenko, Megan Linkin, David Major, Megan O'Grady, Lesley Patrick, Edna Sussman, Gary Yohe, and Rae Zimmerman (2011) "Developing Coastal Adaptation to Climate Change in the New York City Infrastructure-Shed: Process, Approach, Tools, and Strategies." Climatic Change 106(1):93–127.	The purpose of this method is to understand the responses of climate change over time and update the management methods of coastline infrastructures.
38	Rotzoll, Kolja and Charles H. Fletcher (2013) Assessment of Groundwater Inundation as a Consequence of Sea-Level Rise. Nature Climate Change 3(5):477–81.	They investigated the effect of rising groundwater levels on the inundation of coastal regions in the US.
39	Sahin, Oz and Sherif Mohamed. (2013). A Spatial Temporal Decision Framework for Adaptation to Sea Level Rise. Environmental Modelling and Software 46:129–41.	They developed a five-dimensional and time-independent framework to assess vulnerability and adaptation to SLR. Then used it for study of City of the Gold Coast in the state of Queensland, Australia as a case study.
40	Semadeni-Davies, Annette, Claes Hernebring, Gilbert Svensson, and L. G. Gustafsson (2008) The Impacts of Climate Change and Urbanisation on Drainage in Helsingborg, Sweden: Combined Sewer System. Journal of Hydrology 350(1–2):100–113.	The objective of this paper was to investigate the effects of climate change and urbanization on the wastewater system of Helisenborg, Sweden with Danish Hydrological Institue MOUSE simulations.
41	Suh, Jonghae, Alain Tcheukam Siwe, and Samer Michel Madanat (2019) Transportation Infrastructure Protection Planning against Sea Level Rise: Analysis Using Operational Landscape Units. Journal of Infrastructure Systems 25(3):1–8.	They investigated the effects of sea-level rise on the road system of San Francisco Bay assuming the protection systems were unchanged.
42	Turbott, Christopher and Andrew Stewart (2006) Managed Retreat from Coastal Hazards : Options for Implementation. Environment (April):97.	This paper aims to highlight the managed retreat of coastal structures from shorelines, particularly in New Zealand.
43	Walsh, Sean and Robert Miskewitz (2013) Impact of Sea Level Rise on Tide Gate Function. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering 48(4):453–63.	They investigated the effect of heightened sea-levels on a tide gate located in a wetland ecosystem known as the New Jersey Meadowlands.
44	Wang, Ruo-qian, Mark T. Stacey, Liv Muir, Meltzner Herdman, and Patrick L. Barnard (2018) Earth ' s Future The Influence of Sea Level Rise on the Regional Interdependence of Coastal Infrastructure Special Section.	They studied the flood risk to the developing coast of San Francisco with a numerical model based on the assumption of sea-level rise equal to 1.5m.
45	Wdowinski, Shimon, Ronald Bray, Ben P. Kirtman, and Zhaohua Wu (2016) Increasing Flooding Hazard in Coastal Communities Due to Rising Sea Level: Case Study of Miami Beach, Florida. Ocean and Coastal Management 126:1–8.	The objective of this paper was to define the flood risk of Miami Beach through the analysis of historical maps.
46	Xiao, Han, Dingbao Wang, Stephen C. Medeiros, Scott C. Hagen, and Carlton R. Hall (2018) Assessing Sea-Level Rise Impact on Saltwater Intrusion into the Root Zone of a Geo-Typical Area in Coastal East-Central Florida. Science of the Total Environment 630:211–21.	This paper concentrated on intrusion of saltwater into freshwater and the impacts on agriculture in coastal areas.
47	Zhang, Keqi, John Dittmar, Michael Ross, and Chris Bergh (2011) Assessment of Sea Level Rise Impacts on Human Population and Real Property in the Florida Keys. Climatic Change 107(1):129–46.	The authors investigated the inundation of the Florida Keys in incremental sea-level rise scenarios with a digital elevation model and geographical maps.

3. Impacts of SLR on Infrastructures

Some researchers have investigated the effect of SLR on infrastructure systems. Ayyub et al. [5] studied geographic changes and flooding effects on Washington D.C. infrastructures. A linear model of GIS was proposed to define the impacts of SLR on infrastructures and then compare the results of the model with a few nonlinear models. They showed that their proposed model underestimated SLR more than the other models and discussed different scenarios of SLR which could impose serious damage on any infrastructures. Johnston et al. [6] used a multi-criteria analysis (social, economic, health, and safety) to define the risk level of different infrastructures in a coastal region of the U.S. (Scarborough, Maine) due to SLR effects. A GIS mapping system was applied to determine the vulnerabilities of the infrastructure for three different flooding risk plans. The conclusion was that the highways and roads of the town are at high risk of flooding caused by SLR. Thus, adaptation strategies should focus on the aforementioned transport system. Carlson et al. (Carlson, Goldman, and Dahl n.d.) focused on the coastal oil refining systems of the U.S., cautioning that SLR and resulting effects such as storm surges could damage the oil refining infrastructures in coastal regions. Production costs of infrastructures such as gasoline could increase in large magnitudes due to decreased production. The authors concluded that policies should be written and enforced for companies to follow for adaptation and reduction of risk. Joyce et al. [7] studied the effect of SLR on the resilience of the coastal water drainage system with a multi-scale modeling analysis, which is typically used for the analysis of urban water drainage systems. Hydraulic, climate, and geographic information provided scales in the study. The Cross Bayou canal of Florida was modeled as a case study. Wang et al. [8] investigated the effect of coastal change due to human activities on SLR effects. They assessed the flooding risk on the developing coast of San Francisco with a numerical model and assumption of SLR equal to 1.5m. The conclusion was that the coasts of large cities should be adapted to SLR effects, including tidal effects.

3.1. Effects of SLR on Coastal Region Ecosystems and Water/Wastewater Infrastructure

Population density and the consequent development of infrastructures and buildings have been increasing in coastal regions. Hence, urbanization in coastal regions is accompanied by environmental risks. Effects of Sea Level Rise (SLR) on coastal ecosystems and associated infrastructures include increased beach erosion, frequent flooding with long duration, marine and groundwater inundation, saltwater intrusion into freshwater, and increased flow into wastewater networks [9].

Coastal erosion may result from both natural and human-induced factors: waves, winds, tides, storms, SLR, land reclamation, and dredging. SLR is an important factor in determining the profile of sedimentary coasts. The profile of the coast may be represented as a parabola function of the sea-level, as expressed by

$$\mathrm{R} = {}^{S \times L}/_{h_d} + f \tag{1}$$

Where R is a landward translation of the coastal sand, S is the SLR, L is the active length of the profile, h_d is the depth of the closure and f is the freeboard.

The coast profile parabola could be raised as a result of SLR. Extra sand is needed to contract the upper layer of the profile. The extra sand should be supplied from the coastal sands and replaced with water in the deposition layer. Therefore, the level of water is dependent on the deposition of the sand, as shown in Figure 3 [10, 11].

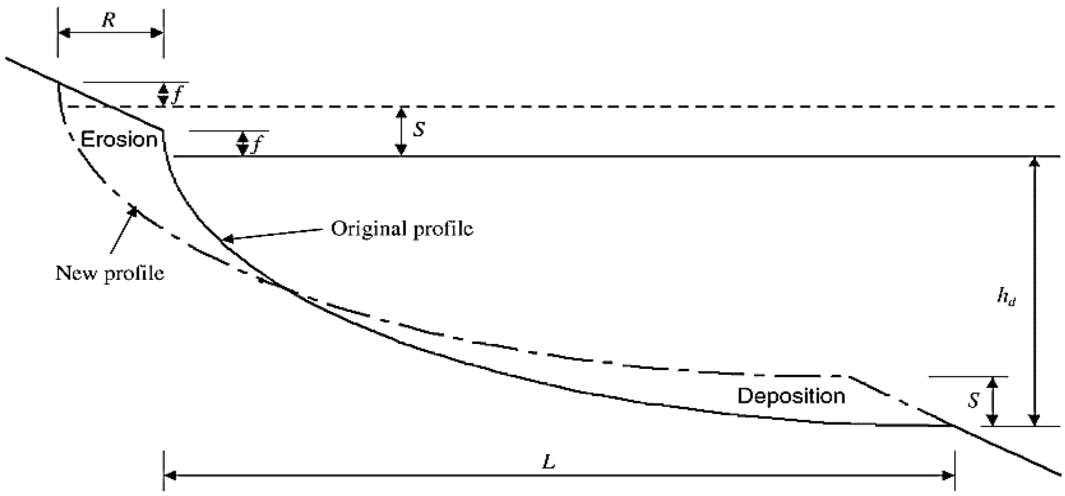


Figure 3. Erosion of beach by SLR [10]

Water supply and wastewater treatment networks could be severely affected by alterations in rainfall and SLR. Increased rainfall and SLR can cause increased frequency and duration of floods. Inundation of lowland coasts and deltas could affect agriculture, groundwater, and infrastructures such as wastewater systems. The flow of saltwater from the sea into a wastewater system could cause damage and increase flow which may bypass the wastewater system [12]. The increased hydrostatic pressure of saltwater due to SLR could cause intrusion of saltwater into freshwater and groundwater resources. Saltwater intrusion could kill salt intolerant vegetation and exacerbate erosion of ecosystems in the coastal belts. Figure 4 shows the intrusion of saltwater into the groundwater of a coastal area. Furthermore, alterations in rainfall amounts due to climate change may alter the hydraulic gradients between land and sea, subsequently resulting in more saltwater intrusion, which would be one of the inevitable stressors to be considered in climate change and hydraulic modeling [13].

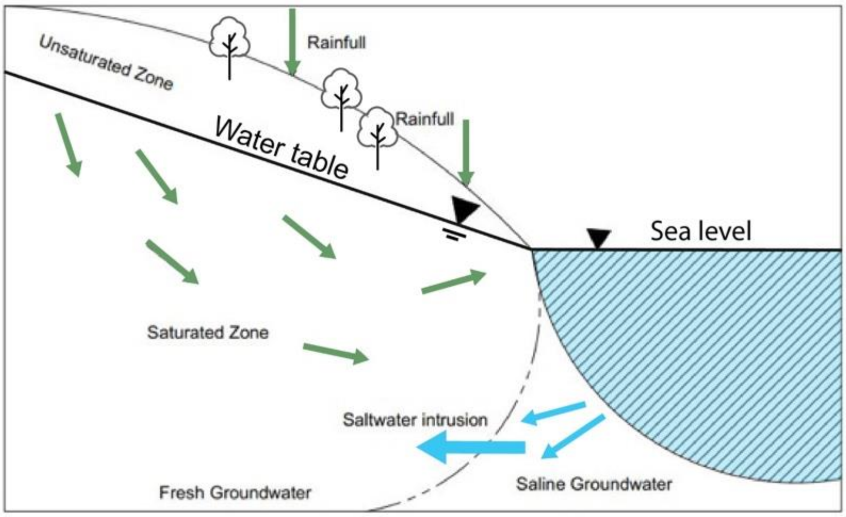


Figure 4. the salinity of fresh groundwater [14]

Another effective parameter in saltwater intrusion studies is the structure of soil grains. Soils of coastal regions are usually considered homogeneous, although some may be nonhomogeneous. Shi et al. [15] investigated a method to consider saltwater penetration in groundwater of a nonhomogeneous coastal region. The researchers modeled the layered coastal regions and compared results from the analytical model with results from an experimental model. Figure 5. shows the simulated model. They concluded that the aquifer stratification could increase the probability of saltwater penetration into freshwater due to SLR in twofold: primary location and/or response interval from the joint toe. The response interval is directly related to hydrodynamic connectivity properties of top layer soils- displayed as a linear function. However, the hydrodynamic properties of low layers do not affect the response interval according to the data. Moreover, the equivalent homogeneous model could not predict the response of layered soil of coastal zones for the intrusion of saltwater. Notably, the inundation effects on intrusion were not included in their study and could be featured in a future research study. Soil characteristics like porosity also have an effect on rising water in coastal cities and need consideration in future research. For instance, water can rise up through limestone in South Florida [16].

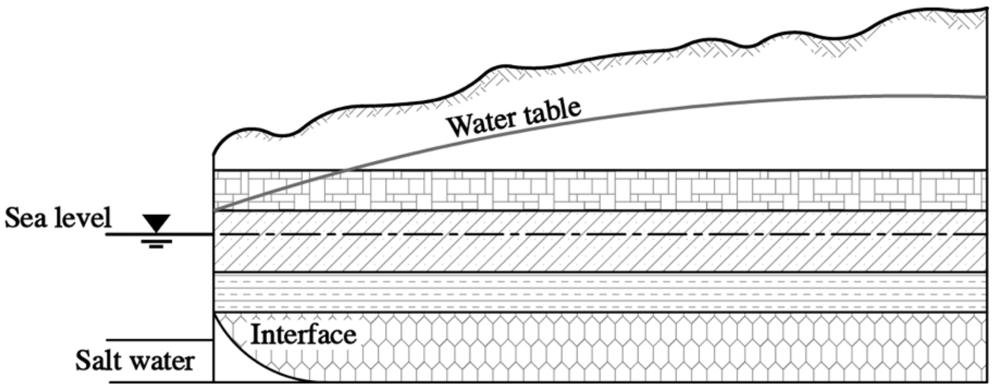


Figure 5. The salinity of layered nonhomogenous soil

Abdoulhalik et al. [13] studied intrusion of saltwater into freshwater in a coastal zone due to SLR. They investigated this phenomenon with an experimental water flow in a laboratory and with an analytical model. Their case studies were two homogenous systems with two differing sizes of grains. The experimental measurements were performed by image processing and the results were verified by SEAWAT, which is a numerical code for solving interface problems of water. The conclusion was that the transfer speed of saltwater is twice the needed time for freshwater retreat.

3.2. Transportation Infrastructure

Sea level rise is a challenging issue for infrastructure that increases the number of floods, number of storm-surges, and amount of beach erosion affecting seaport cities. Transportation activities are highly affected by these consequences, which lead to a series of effects that could affect the entire network of transportation in a district. Therefore, analyzing the impacts and adaptation strategies in previous studies would be beneficial to understand the vulnerability of transportation assets and to identify protective measures. This section will elucidate different transportation configurations categorized as Roads, Ports (Air and Sea), and Underground facilities (Metro, Tunnel and Drainage system). [17-19].

3.2.1. Impacts of Rail Infrastructure

Potential impacts of climate change and SLR on the performance of transportation infrastructure need more attention [20-22]. Governments and policymakers around the world have reached the conclusion that in order to protect a city from various weather-related events, a resilient transportation infrastructure is required. Study findings [23] depict that climate change adaptations should be in congruence with mitigation approaches and investing in transportation infrastructures is important for addressing existing concerns and preventing future problems.

Many studies confirm that SLR is a major concern for coastal areas. A combination of SLR and extreme rainfall increases the frequency of coastal flooding. This issue is exacerbated by an increase in winds and low atmospheric pressure, which cause storm surges. The effect of storm surges can be more devastating with high tides [21]. For instance, storm surge in April 2013 on the North Sea coast of the UK was 2 meters above the predicted high tide and caused disruption. The majority of megacities in the world (cities with more than 8 million populations) are located in coastal areas. Transportation infrastructures (ports, airports, rail, and roads) are at high risk in these cities, lowland areas, and transportation corridors.

Vulnerabilities of rail infrastructures have been identified around the globe. [20, 21]. Dawson et al. [21] applied a semi-empirical modeling approach to identify correlations of SLR and rail incidents during the last 150 years and used model-based SLR prediction to anticipate future relationships. In a particular case study of Dawlish, a coastal town in England, different adaptations were evaluated. A cost analysis assessment determined that maintenance or abandonment of the railway would be less expensive compared to damages from any extreme events and compared to modification of the rail system. Changing the rail path was determined to be the most expensive solution.

Water standing/inundation: In October 2004, the westbound track near London experienced a five-day shutdown and a foot of standing water on the track bed was confirmed to be a major reason for this closure. Other types of damages to the rail infrastructure could occur based on different scenarios of rising sea-level. Service disruptions can be caused by damage to the structural integrity of the rail components like ballast washout, subsidence or depression of the track, station platform overtopping, platform lift up, and severe damage to breakwaters/walkways/footpaths. Damage can extend to the retaining walls and seawalls along rail roads.

3.2.1.1. Adaptation in Rail Infrastructure

Soft protective measures like cliff stabilization, dune regeneration, beach nourishment, and coastal realignment in contrast to hard protective sea defenses like sea walls, rock armor, and breakwaters have been utilized to protect coastal cities [24]. In Britain, only 1200 km of the coastal defense structure prevents water from flooding the coastal land. This number is about one-third of the coastline in England. These defense structures have been designed based on the statistical return period of the extreme events; hence changes in the sea-level height will have significant impacts on estimation of the return period's variables. SLR significantly increases the risk of flooding on the coastal shores [21]. This conveys the importance of the actual SLR estimation in the future planning of port cities. Many attempts have been made to understand relative SLR by considering land subsidence, uplift, and glacial impact (glacial-isostatic adjustment (GIA)). For instance, the creation of spatial patterns through these parameters demonstrates that the southwest of England will experience the highest relative SLR in England during this century.

One problem with sea walls, especially during storm seasons, is breaching of the seawall along the coastline. If a seawall protects railroads or roads, any damage from breaching might result in road closure or blockage for months. The reliable dimension of the resilient civil infrastructure system can be obtained with the application of various approaches. Maintenance of a line is considered an internal cost, whereas indirect (external) costs include increased travel time, changes in the timetable, decreased tourism bookings, and reduction in the level of service in the entire transportation system. Travel time is directly associated with GDP and any disruption in transportation infrastructures has negative consequences on an economy [21].

The cost-benefit ratio method has been applied to assess the monetary value of travel time. Another type of cost to rail infrastructure (introduced in early 2014) is called "wear and tear", which is associated with extreme catastrophes and huge damages to the infrastructures. Train operators in some countries may compensate for these inconveniences and provide other methods of commute for the passengers. The socio-economics of communities is directly related to the reliability of the transportation infrastructures like railways and roads. For instance, the winter storm of 2014 in England caused a two-month closure of the rail system and Network Rail Company ascertained that reopening the existing railroad would be more cost-effective than building a new railroad. Most overtopping events have occurred in the low-lying areas along the shores. With a high-SLR scenario, these delays are projected to cost an estimated 1.1 million pounds by 2040 based on the current rate.

Numerous parameters (wave process, hydrological process, geometric designs, structure materials, storm intensity, storm frequency, low air pressure, etc.) may be considered to evaluate the workability or design of a seawall against SLR. Modeling of these parameters includes some uncertainties which add complexity (e.g. estimates of future water heights). Different numerical, semi-empirical methods have been used to model and estimate rising sea-level trends.

Various adaptation methods are considered in the assessment of transportation infrastructure. Inaction, protection of the existing line, and construction of new facilities are options to be assessed with price estimation. According to Dawson et al., the Adriatic coast has invested two billion pounds to decrease the vulnerability of the transportation access road [21]. In another attempt, a line along the Ligurian Sea has been relocated inland and a tunnel protects the railway. Of course, transportation investment appraisal is subject to change since the magnitude of future SLR is uncertain. Tide-gauge records in many cities like Boston, New York, London, Miami, Sydney, Bangkok, and Mumbai have been useful tools for recording SLR and assessing vulnerabilities of transport infrastructures. Tide-gauge record data has been utilized in many semi-empirical approaches. It should be mentioned that sufficient evidence is necessary to validate empirical trends in SLR.

3.2.1.2. Response to the Threat of the Incoming Storm

One of the approaches to storm response that has been used in the UK is applying restrictions to train service. Restrictions vary based on level of severity and may result in full closure of the lines. Installed sea-sensors reveal information regarding overtopping events to managing staff who can enforce restrictions to avoid dangers.

Because most transportation infrastructures are owned and managed by various agencies, protection of these urban systems creates conflicts of interest and may increase response time to any hazard due to lack of coordinated involvement and communication between national, regional, and local agencies. However, multi-jurisdictional management can offer more attainable solutions and unite stockholders together [9, 21, 24, 25].

3.2.2. Roads (Corridors)

Among different types of transportation infrastructures, roads are the predominant mode of daily commutes and are vulnerable to SLR over time. Agencies such as the U.S Climate Change Science Program (CCSP), ICF, and the Department of Transportation (DOT) assess impacts of SLR and the effects of inundation on different types of transportation infrastructures [15, 20, 26]. On the coastal strip, SLR may cause road material degradation, decreased level of service, decreased accessibility due to erosion of the base of roadways, increased travel time and fuel consumption due to traffic saturation conditions and re-routing, compromised safety of the network, decreased drainage capacity, and ineffective traffic management. In low-lying coastal zones, especially densely populated areas, a minor network disruption creates many difficulties for those reliant on that network. Therefore, adaptive design and novel performance assessment for infrastructures (such as design standards, design guidelines and building resilient facilities) are necessary [19, 20].

The dominant concerns regarding SLR for corridors and roads are recurrent traffic congestion, vulnerability to frequent flooding, and vulnerability of environmental resources in close vicinity to the roads. Closure of coastal routes could result in severe traffic congestion and backlogs. Inundation and diversion of traffic flow induces congestion of entire transportation paths. Figure 6a shows vicinity of U.S. Route 1 in Malibu, California to the ocean and even with low SLR scenario, this road will be flooded. Stone groins were installed to protect the beach from erosion (Figure 6b). Authoritative agencies will need to perform comprehensive assessments of vulnerable routes and implement design strategies. Traffic demands and the peak times for high traffic must be considered in the analysis of an area to plan improvements in road infrastructures. Green adaptation (nature-based) methods involving the evaluation of ecological parameters and evolving landscapes will result in more integrated solutions. In the assessment of any solution for SLR, any negative impacts on the investment, public access, and recreational facilities should be taken into account. Taking action may be time-sensitive and collaboration between authoritative agencies is very important for risk assessment and evaluating feasibility of solutions.

a) U.S. Route 1 California

b) Groins (hydraulic structures) to protect sediment erosion in the ocean shore

Figure 6. Vulnerability of roads to SLR and Adaptations (December 2018)

3.2.2.1. Impacts on Roads

Various factors should be taken into account for SLR risk assessment: capital improvement costs, economic impacts on travelers, transportation of products, effects on the economy, and impacts on adjacent paths in a network, to name a few. An inundation map exhibiting which segments of a road or network will be inundated in different SLR scenarios is a helpful tool for decision making. Rainfall-runoff events, hydraulic structures like culvert and tidal gates, and FEMA's storm surge estimates can be considered by an inundation map.

Suh et al. [27] investigated the impacts of SLR on the road infrastructures in San Francisco Bay, assuming no changes in protection level to infrastructures against SLR risks. The study considered 0.5m of SLR in a scenario simulated with the CosMos method. The case study region was divided into homogeneous sections and an agent-based approach defined the advantages of protecting San Francisco Bay from SLR. The combined method of simulating traffic and hydrodynamics effects determined the region is at high risk of inundation due to flooding. However, only traffic of motor vehicles was included; other types of transportation infrastructures were excluded from the study. Another limitation is that a levee was evaluated as the only protection system against SLR threats.

3.2.2.2. Adaptation on Roads

Levees are an adaptation method for SLR, daily tidal inundation, and storm surge flooding. Because Route SR-37 in San Francisco Bay area was closed for 28 days in January and February 2017 due to flooding, Caltrans spent $8 million on flood prevention. Caltrans used lightweight material to increase height of the road by 2 feet and cross-highway culverts were replaced. The raised portion of the segments function as levees. (Route 37 AECOM report). Levees owned by the private sector have protected residential and commercial properties and roads sometimes take advantage of these facilities. Designated authorities like DOTs should take responsibility for managing, inspecting, maintaining, and evaluating the operation of these levees and identifying the places most vulnerable to flooding in order to ensure route serviceability. The State of California SLR Guidance Document (2013) recommends longer life span for critical infrastructure based on the highest SLR rate plus the 100-year storm plan design consideration. These scenarios may be added to the design codes at the global level [28].

Studies focusing on SLR impacts on the energy facilities of coastal zones are scarce; investigations are much needed to understand SLR impacts and to improve planning and adaptation options.

Impacts and adaptations of SLR to transportation infrastructures can be summarized as follows:

Impacts:

- Permanent Flooding
- Greater coastal storm strength with SLR
- Loss of barrier islands
  - Land subsidence
  - Loss of coastal wetlands and barrier shoreline
  - Reduced clearance under bridges
  - Bridge scour
  - Erosion of road base and bridge support
  - Low-lying bridge and tunnel entrances for roads, rails and rail transit will be more susceptible to flooding

  - Inundation of roads and rail lines in coastal areas
  - Culverts could be undersized for flow
- Protect with levees/dikes/seawalls
- Elevate critical infrastructures
- Abandon or relocate threatened facilities to higher elevation
  - Analyze transportation system vulnerabilities to potential storm surge
  - Include climate change assessment in long-term transportation planning in floodplains and in land use planning in flood-prone coastal areas
  - Identify and take constructive action to provide and protect emergency evacuation routes
  - Protect critical components- tunnels, electrical systems
  - Retrofit to strengthen tie-down bridge decks, protect piers against scour
  - Construct surge barriers to protect vulnerable rivers and adjacent infrastructure
  - Update FEMA flood maps based on the climate change
- Protect or relocate newly exposed railroads, highways, bridges
- Switch to alternate shipping methods if waterborne transport cannot use the Intracoastal Waterway or other shipping channels
- Raise bridge heights and reinforce or relocate harbor infrastructure
- Establish an adaptive standard to implement during regular maintenance and rebuilding of facilities

Table 2. Adaptations of sea level rise on roadways network

Vulnerable Segment	Adaptation
Protect Roadway Base	• Increase Storm water drainage system capacity • Increase the number of pumping stations, drain roadway right-of-way • Identify off-site storm water retention area to divert excess storm water • Eliminate exfiltration trenches as a drainage solution • Install WellPoint dewatering technology for permanent use • Raise roadway elevations
Protect Roadway Surfaces	• Increase roadway storm water activity • Elevate roadway surface 5 feet above mean high tide (minimum 10 ft. NAV88) • Relocate critical roadways • Re-route traffic, freight and transit routes
Abandon Roadway	• Abandon low areas which cannot be elevated without private property impacts • Abandon state roadways or local right of ways
Stormwater Management	• Reengineer canal systems, control structures, and pumping stations
Provide different modes of transportations	• Transit (Provide urban and intercity transit services/ Provide accessibility and connectivity to and from transit centers/ Increase transit route coverage and frequency/ Promote transit patronage) • Freight (Evaluate logistics and schedule / Re-route existing freight routes/ Institute short sea slipping among ports to decrease traffic load on local infrastructures) • Other (Promote use of non-motorized vehicles/ Provide connected bicycle and pedestrian paths/ Promote rail and other transit methods/ Promote alternative fuel and fuelling infrastructure/ Provide special attention to adaptation on critical evacuation routes/ Increase use of the canal network for transportation)
Policy	• Provide federal incentives to avoid development in floodplains • Institute better land-use planning • Recognize the inherent cost of construction in flood-prone areas

3.3. Effects of SLR on Energy Facilities of Coastal Regions

Energy equipment in the coastal region is usually constructed in low land zones and performance may be compromised by SLR effects. Oil refineries and nuclear power stations are two important examples of energy equipment. Failure of this equipment has many costs for energy consumers, maintenance is expensive, and malfunction can lead to environmental pollution. SLR effects could even cause explosion of the equipment, which endangers lives. One of the most recent nuclear plant failures was the Fukushima nuclear disaster caused by the 2011

Japanese tsunami. Studying effects of SLR on energy facilities is vital; however, few research articles have actually focused on this subject.

Brown et al. [24] studied the effect of SLR on the energy infrastructures in Europe. The GIS was used to investigate the impacts of SLR on energy infrastructures such as oil, gas, and LNG tanker terminals and nuclear power stations in coastal regions. Planning and adaptation options were discussed in the study. The authors concluded that the energy facilities of countries in northwestern Europe are most at risk for SLR compared to other European regions and advised that governments of those countries should study vulnerabilities and adaptations for the energy infrastructures in coastal zones.

Dismukes and Narra [29] studied the direct effects of SLR on energy systems of the U.S. Gulf Coast and tested adaptation options for these systems. According to their research, natural gas transmission systems are more vulnerable than other systems such as oil refineries. The authors advised that protective adaptation systems should be improved for increased resilience against the impacts of SLR effects on the energy systems.

Jenkins et al. [30] studied the effects of SLR on nuclear plants and spent fuel storage systems located in coastal regions of the U.S. further inland from the coastline. Satellite images and governmental databases were employed to define locations of nuclear plants and coastline. The magnitude of SLR was predicted by imaging the increase in sea level and monitoring databases. Gathered information was imported to geospatial mapping software (QGIS) and analyzed to define levels of SLR vulnerability for nuclear facilities. The research proposed several strategies to protect nuclear facilities, such as transfer of fuels into safe regions.

The rest of the article focuses on specific coastal regions, describing impacts and adaptations in these areas.

3.4. Effects of SLR on Coastal Zones of Asia

Asia has the largest coastline of the world located adjacent to the Arctic, Indian, and Pacific oceans. Several countries in Asia are comprised of one or more lowland islands, such as the archipelagos of Indonesia and the Philippines. The coastal zones of Asia are the most populated areas around the world [3]. Thus, the effects of climate change, such as increased rainfall and SLR, could affect the lives of innumerable people in Asia.

3.4.1. Flooding, Inundation, Beach Erosion and Groundwater

Jallow et al. [31] studied the vulnerability of the coastal zone of Gambia- a country with 70km of an open ocean coast. The researchers used the Aerial Video-tape-assisted Vulnerability Analysis (AVVA) method to define the SLR vulnerability in detail, determining the type of coasts, use of the lands, and infrastructures by video recording. The land loss due to beach erosion, flooding, and an increase in groundwater level was estimated based on a 1m SLR scenario.

The height from sea-level of islands in the Pacific Basin is usually less than five meters (lowland islands). Thus, SLR could inundate large areas of the islands. Pernetta [32] asserted that governments are tasked with protecting these vulnerable islands from SLR effects. Since greenhouse gases are the fundamental reason for anthropogenic global warming and SLR, industrial countries are predominantly causing the phenomena. Pernetta contends that industrial countries should consequently be held financially responsible for expenses of protection programs for the islands and the independent governments of the islands must advocate for the reduction of greenhouse gas emissions by industrial countries.

Neumann et al. [4] investigated the effects of SLR on the Red River delta in Vietnam under storm and flooding conditions. The Red River delta is located in the northwest South China Sea. The researchers simulated storm activity to generate wind profile data, utilized the SLOSH model to predict maximum surge levels, and applied three heights of SLR to the models in order to forecast inundation of the delta area. The simulations predicted about 40% of the region to be at risk of permanent inundation and episodic flooding below five meters and 10% of the region to be at risk below the one-meter height predicted for 2050. Proposed adaption strategies included retreat and construction of a seawall and dike system.

Awang et al. [33] estimated the probability for the inundation of the Pahang coast of Malaysia under SLR scenarios for 2020 and 2080. The hydrodynamic flow of seawater was numerically modeled with MIKE 21 FM software that could be used to simulate 2D and 3D flow models [34]. The results convey that 17 and 22 percent of the studied area will be inundated by seawater in the years 2020 and 2080, respectively. However, the researchers mentioned that the studied area has an increased rate of erosion and the effect of rising sea-level on the erosion was not accounted for in the study. Ehsan et al. [35] emphasized the effects of erosion and flooding which threaten the populated coastal zones of Malaysia. The article details observed and projected estimates in sea-level rise from the IPCC and the National Hydraulic Research Institute of Malaysia (NAHRIM).

Mimura [36] studied the vulnerabilities of lowland island countries of the South Pacific to rising sea-level, reiterating that inundation and flooding are important risks. Because of the small contribution of island countries in the production of greenhouse gases, adaptation is essential for preventing SLR effects. Adaption alternatives were categorized into three groups: community education and involvement in planning initiatives, technical options such as designed seawalls with preservation of existing natural barriers, and policies for land use and environmental conservation.

Liu et al. [37] investigated different patterns of erosion on the coasts of the Taiwan Strait. Historical topographical maps from various years were superimposed to measure coastline erosion and estimate the rate of erosion. According to historical data and present morphological observations, the contributing factors of coastal erosion were determined to be SLR, river sediment discharge reduction, human activities, storm surge, and cliff composition. According to the primary data collected through field studies, the most severe immediate causes of erosion in the studied area were sand mining, storm surge, cliff composition, and coastal construction.

Recently, Griffiths et al. [38] studied the effects of SLR on an urban drainage system in Southeastern China for predicting flooding probability. The region is at high flood risk due to low elevation of coastal areas, frequency and intensity of tropical typhoons from the Western Pacific Ocean, and urbanization causing increased runoff. The researchers designed a model for a canal and sluice-gate system and applied a Monte Carlo method to evaluate the performance of drainage channels with different water and tidal levels. Data from several storm events were applied to the model to assess predictability and duration of flooding. This modeling could be further developed and applied to other coastal regions to predict flooding due to SLR and to analyze mitigation methods for reducing the impacts of flooding.

Chun et al. [39] investigated the intrusion of saltwater into underground water by analyzing the recharge rate of freshwater and SLR. The data was gathered by monitoring groundwater level, temperature, and electric conductivity at locations of saltwater intrusion at the Gunsan tide gauge station in South Korea. SLR projections were modeled for the 2050s and 2090s by two polynomial regression methods: linear and quadratic. The saltwater intrusion was examined with the Saturated-Unsaturated Transport (SUTRA) model, which is based on finite element and finite difference methods in MODEL FLOW software (USGS Groundwater Information 2005). The researchers concluded that the recharge of freshwater could have a significant effect on intrusion in values greater than a specific rate of recharge, recommending that SLR and recharge of fresh water should be included in investigations of saltwater intrusion in the freshwater of coastal regions.

Saltwater intrusion and increased salinity of freshwater are potentially devastating consequences of SLR. The Mekong Delta is the most productive agricultural region in Vietnam, with most land designated as rice fields. This region produces almost all rice exports in a country with a rice-based economy. The Mekong Delta is an area of low elevation and salinity intrusion has damaged crops and caused drought, resulting in extensive economic losses. Vu, Yamada, and Ishidaira [40] investigated the intrusion of seawater into fresh groundwater due to rising sea-levels in the Mekong Delta. The researchers applied a one-dimensional numerical model named MIKE to simulate SLR scenarios and estimate salinity concentrations in the groundwater due to salinity intrusion. A 25 to 30cm rise in sea-level was assumed in their model based on the predicted SLR for 2050. The results indicated that four of the eight agricultural provinces would be seriously damaged by salinity intrusion. Medium salinity, defined by more than 4g/l of salt, was estimated to represent a loss of approximately 240,000 tons of rice. The model could be improved by accounting for topography and cross-section.

3.4.2. Adaptation Options

Adaptation response to climate change for coastal management has been categorized by the strategies of protection, accommodation, and retreat [41]. Protections are preventive structures to prevent flooding and erosion. Hard protection consists of hard structures that provide a barricade against the inflow of water. Soft protection includes natural barriers of sedimentation and forests in addition to wetlands that create a buffer zone. Accommodations pertain to reducing the severity of damages, such as elevation and modification of properties and infrastructures to reduce the impact of flooding. Retreat from the coastline is the relocation of coastal properties and infrastructures more inland and further away from the coastline to reduce vulnerability. Retreat policies and planning require changes in land use and allocation [42].

Adaptation alternatives may be sorted into three sub-groups: community education and involvement in planning initiatives, technical options such as designed seawalls with preservation of existing natural barriers, and policies for land use and environmental conservation.

- Green adaptations: green infrastructures and natural barriers such as coral reefs, mangroves, and wetlands
- Gray adaptations: seawalls, dikes, pump stations, elevated roads and bridges, levees and gates, and storm surge barriers
- Pink adaptations: policies, land use allocations, education, and social involvement

Hill [43] discussed the advantages and disadvantages for some of the combined adaptation methods (i.e. structural and nonstructural). In sandy and marshy regions, costal infrastructures were constructed as rigid landforms which needed a lot of excavation or installation effort (for example superbike which was built in Osaka, Japan). The current type of these landforms are categorized in two groups: rigid landforms (like levees and mounds); and dynamic forms which changes during the time. The sand engine project along the Dutch coast is an example of this approach. The author presented a 2D diagram to elaborate the topology-based approach in SLR adaptations based on the percentage of physical infrastructure, which varies from sea wall to landforms verses percentage of design components (static vs dynamic). The dynamic part of the diagram demonstrates the situation that evolves and changes during the time, but the static portion of the diagram depicts permanent adaptations. Figure 7 illustrates this figure. Based on the article, dynamic landforms like beaches and marshes have not a specific level of duty and their type depends on the location and time. However, a dynamic approach could save habitat and ecosystem. In addition, a dynamic method doesn't need all the effort once to build the infrastructure and because of loose material, there is no need to replace the original structure in future attempts.

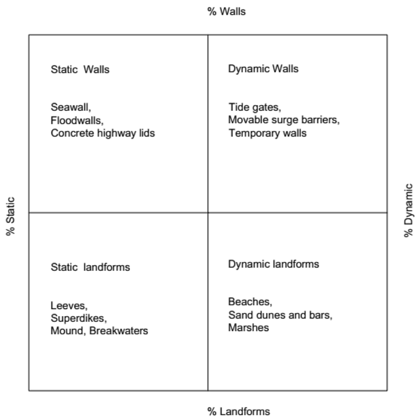
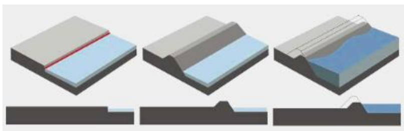
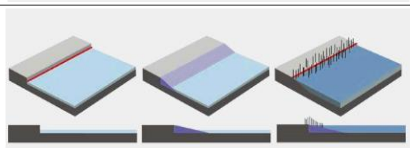
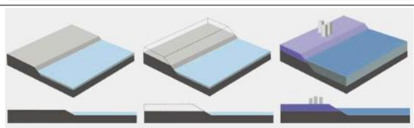
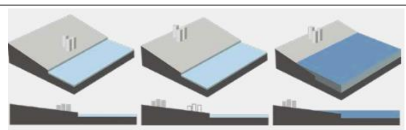
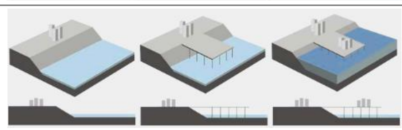


Figure 7. Topology based diagram for sea level rise [43]

Lee [44] recommends planning strategies for urban development resilience to SLR. The study site selected is the city of Mokpo in South Korea, a city which experiences frequent flooding and is especially vulnerable to inundation. The proposed strategies include multi-tiered terraces, construction of earth mounds, sloped buffer zones of vegetation, and relocation of urban developments. The multi-tiered terraces and earth mounds would predominantly provide hard protection of vital infrastructures, whereas the buffer zones of vegetation and wetlands are adaptive for temporary inundation, as shown in Figure 8.

Figure 8. SLR Adaption Strategies in coastal regions [44]

Strategies		Features	Methods	Site Advantages	Diagrams
Protection or defence	Hard	Dikes Levees Sea Walls Groins	Build physical barriers to block water	or hard-to-move facilities and infrastructure on flat ground	
	Soft	Mangroves Wetlands Sand dunes Tidal Flats	Create buffer with vegetation or landforms	For maintaining shoreline at sites with existing coastal forest or sand dunes	
Accommodation		Raising level Desalination Drainage Alarm system	Upgrade functions while maintaining location	For redevelopment projects or facilities at sites without high ground nearby	
Retreat		Relocation Abandonment	Relocate facilities to low-risk uplands	For residential and public facilities at sites with low-risk uplands nearby	
Attack		Land Reclamation Piers Ports Harbors	Extend facilities towards water	For facilities requiring direct access to water	

3.5. Effects of SLR on coastal zones of Oceania

Located in the Asia-Pacific region, Oceania is comprised of three island countries: Australia, New Zealand, and New Guinea. Several large cities such as Melbourne and Sydney are located on the coast of Australia adjacent to the Indian and Pacific Oceans. An estimated 85% of the population in Australia lives in coastal zones [45]. The International Panel on Climate Change predicted increasing storm surge and SLR affecting the Australian coastline (Carter n.d.). Several researchers have contemplated strategies for planning mitigation and adaptation measures to address SLR.

3.5.1. Adaptation Options

Turbott and Stewart [46] wrote extensively about the managed retreat of coastal structures from shorelines, particularly in New Zealand. Managed retreat refers to government intervention to regulate the relocation and abandonment of property. Interventions listed included government regulation in the district, regional, and national legislation, financial instruments, and distribution of information regarding options for managing coastal hazards, and involvement in decisions about public infrastructure. Structures may be relocated within a property or to other sites and the authors state that large-scale relocation or redevelopment of communities may be necessitated. Financial instruments consist of the governmental purchase of property, subsidies for relocation, and a payment program for relocation funds. According to these implementation guidelines, the main options for the managed retreat are relocation within existing properties, transfer of property ownership by means of government purchase, and confining property rights to a fixed term of use.

Abel et al. [47] considered the application of a development framework to an area of Queensland, Australia and composed general governance principles for the organized retreat. The proposed principles included: dividing authority and resources between levels of government, establishing rules and incentives that provide feedback systems, setting conditions for rules to allow for modification and adaptation, legislating and implementing liability and planning policies for more responsible land use and development, and formalizing a response in anticipation of catastrophes associated with SLR.

Analytical tools such as GIS, simulation tools, and expert systems are very useful in the appraisal and management of environmental problems. These tools are generally applied to the one-dimensional aspect of management. However, environmental problems such as SLR are highly complex and characterized by multiple dimensions. Methods that can simulate multidimensional factors are much needed for the management of coastal zones. Sahin and Mohamed [48] developed a five-dimensional and time-independent framework to assess vulnerability and adaptation to SLR. Figure 9 displays the dimensions of their proposed spatial-temporal model. The City of the Gold Coast in the state of Queensland, Australia was chosen for a case study. Flood maps were produced for a period of 100 years for three rates of SLR: 0.5, 1, and 1.5 cm of increased height per year. The percentage of landscape in the studied area inundated for 2100 was predicted to be approximately 6% for .5 cm, 34% for 1 cm, and 56% for 1.5 cm of SLR per year.

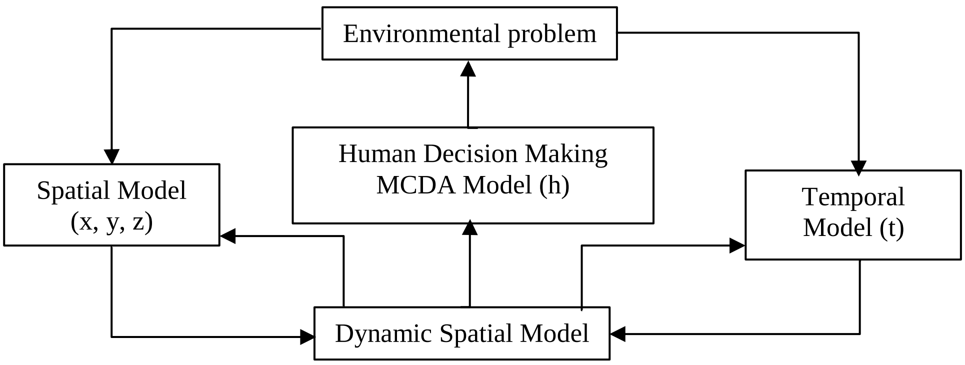


Figure 9. Five dimensions framework of adaption for SLR [48]

3.6. Effects of SLR on Coastal Zones of Europe

3.6.1. Flooding, Inundation, Beach Erosion and Groundwater

An inlet is a small, narrow branch connecting a river or sea to tidal zones. The increasing height of sea-level could affect the inlet and water drainage of tidal regions. Dissanayake, Ranasinghe, and Roelvink [49] focused on the morphological response of a tidal region inlet to SLR effects. The Ameland inlet was selected as a case study. This inlet is located in the Wadden Sea between two barrier islands (Ameland and Terschelling) which are adjacent to the northern coast of the Netherlands. The leading causes of SLR in the Wadden Sea are climate change and tectonic plate movement. Dissanayake et al. [49] used the Delft3D model, which was developed to simulate multidimensional flow. They investigated three scenarios for the time period between 1990-2100: no SLR and no land movement, low SLR equal to 0.2m and land movement, and high SLR equal to 0.7m and land movement. The model indicated that with high SLR, the tidal flats may degenerate into a tidal lagoon. The second scenario of low SLR seemed to represent a tipping point for the stability of tidal flats. For the third scenario of high SLR and land movement, the model predicted the tidal flats would be drowned, indicating the formation of a lagoon. According to the data, erosion and accretion rates are directly related to the rate of SLR.

Some researchers and authorities have used the Bruun Rule to define the relationship between the response of shoreline and SLR. The Bruun Rule is a simplified two-dimensional model that does not consider many geological factors. Cooper and Pilkey [50] studied the limitations of using the Bruun Rule for estimation of coastal retreat under SLR conditions. They summarized the problems and limitations of the Bruun Rule, concluding that the assumptions for deriving the rule are incorrect. The researchers insist that this method for estimating shoreline response in coastal zones under SLR should be abandoned.

Semadeni-Davies et al. [51] investigated the effects of climate change and urbanization on the wastewater system of Helisenborg, Sweden with Danish Hydrological Institute MOUSE (Model of Urban Sewers) simulations. The simulations were modeled for present conditions, climate change scenarios based on rainfall records, and urbanization narratives based on demographics and water management. Increased precipitation would be expected to increase runoff and thus increase stormwater flows and sewer infiltration, reducing capacity and causing an overflow of the combined sewer system. Urbanization is predicted to increase and overflow independently of climate change. In combination, climate change and urbanization would predictably result in drastically increased flow volumes which could necessitate another overflow system.

3.6.2. Adaptation Options

Tidal deltas provide protection to coastlines and facilitate the transport of sediment away from estuaries. The sand waves of Ebb delta systems function as wave breaks, reducing wave energy along shorelines. Therefore, tidal deltas may be used as defense mechanisms. The delta and sand waves can widen in range along the shore as sea level rises for more protection of adjacent shorelines. Data indicates that with increasing sea-level height over time, a tidal delta will extend the accretion/erosion boundary on the shore. This increased size of ebb-tide deltas provides a natural mechanism for self-sustaining coastal defense.

Tide gates close during incoming tides for flood prevention and open during outgoing tides for draining. Higher sea-level heights alter hydraulic gradients, thereby decreasing the functionality of the tide gate system. Walsh and Miskewitz [52] investigated the effect of heightened sea-levels on a tide gate located in a wetland ecosystem known as the New Jersey Meadowlands. Model predictions were formulated with the HEC-RAS and HEC-HMS model. Different scenarios were based on variations in storm data and sea-level height. The data indicated that an increased mean sea-level may cause prolonged flood durations when the hydraulic gradient is not enough to activate the opening of the tide gate. The results specifically stated that increased sea level elevation above 100 cm would cause prolonged flood durations.

3.6.3. Salinization of Freshwater

Fletcher et al. [25] investigated the salinization of freshwater wells due to SLR on the Swedish island of Oland. They studied the region with a GIS map by considering the 2m SLR scenario. The research focused on both the inundation of wells and intrusion of saltwater into freshwater wells. The drawn risk map showed that approximately 5% of the land area and 3% of the wells are at inundation risk. Approximately 17.5% of the wells were categorized as being at high risk and 64% of them at medium risk. The researchers suggested digging new wells in low-risk zones to supply fresh water.

3.7. Effects of SLR on Coastal Zones of USA

3.7.1. Flooding, Inundation, Beach Erosion and Groundwater

Rotzoll and Fletcher [25] investigated the inundation of coastal regions in the U.S. due to the rise of groundwater levels caused by SLR. The level of groundwater is high in coastal regions and thus the rise of sea-level could increase the pressure of saltwater underneath the land. Therefore, freshwater and saltwater interface shifted higher up the coast and hence groundwater inundated the coastal low lands. Figure 10 shows this phenomenon in a coastal region. Rotzoll and Fletcher concluded that the groundwater could inundate 10% of the coastal regions of Honolulu, Hawaii [53].

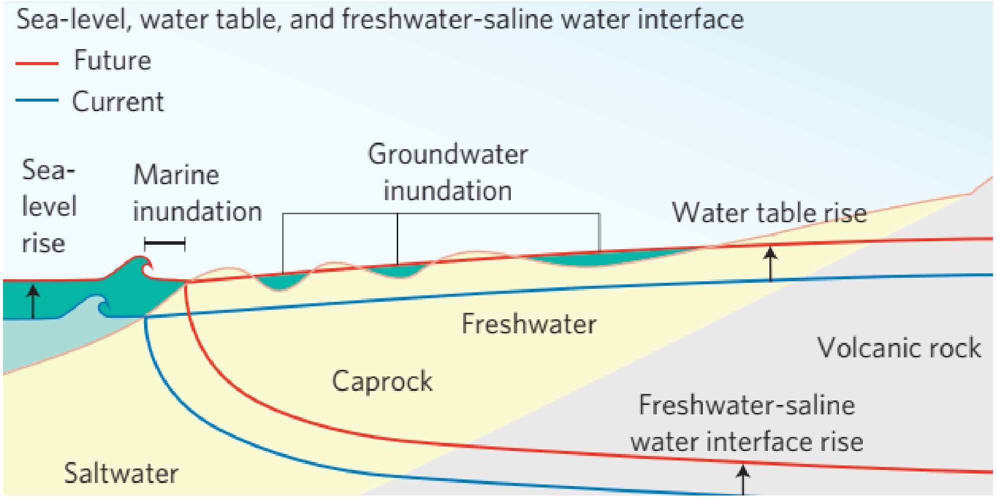


Figure 10. Groundwater inundation [25]

Buzzanga [54] studied the SLR impacts on groundwater in the coastal region of Hampton Roads in southeast Virginia. He applied the coupling of the results from two models to determine the response of the groundwater table under rainfall and SLR conditions. The groundwater flow was simulated by the Unsaturated-Zone flow package with MODFLOW-NWT [55] which used the Newton-Raphson method for solving water flow problems. The surface water model SWMM was applied to simulate rainfall and runoff flow in the studied area. Results demonstrated that the level rise of groundwater could damage the subsurface infrastructures. Moreover, the data supported that the low penetration of soils of the region reduces the runoff water threat for subsurface infrastructures.

Flood and Cahoon [56] investigated the SLR and climate change effects on coastal wastewater collection networks in North Carolina. They studied the increasing water flow in the network due to flooding (inflow) and groundwater penetration in the network from the cracking of pipes (infiltration). A series of recorded data of rainfall and multi-regression of the data was applied for the analysis. The analysis suggested that increased flow into the wastewater network could decrease the efficiency of the treatment system, the flow of saltwater into the network could harm network components, and exceeding flow capacity would create bypasses.

Hummel, Berry, and Stacey [19] analyzed the impact of both marine and groundwater inundation on wastewater treatment infrastructures of coastal regions. Geographic information for the case study area was collected using National Oceanic and Atmospheric Administration (NOAA) data, the Coastal Storm Modeling System (CoSMoS) was applied to model SLR, and a linear relationship between groundwater rise and SLR was assumed in the model. The model predicted that the number of people losing their wastewater drainage service during an inundation is five times more than previously estimated statistics. The authors contended that studies of coastal wastewater infrastructure resiliency should include both marine and groundwater inundation.

Allen et al. [57] studied the effects of SLR and the vulnerability of water and wastewater networks in North and South Carolina. The study linked the effects and the vulnerability of water and wastewater infrastructures with public health infrastructures. The designed geospatial model included sea-level, tidal levels, heavy rain, flooding, and vulnerability of wastewater and underground water systems. Results exhibited that the effects of SLR threaten public health and health infrastructures such as hospitals in the coastal regions. The researchers suggested coastal wastewater systems should perhaps be integrated into centralized systems. The results accentuated the importance of coastal geospatial data, particularly vertical data, and emphasized that in addition to protection, accessibility to pumps and power utilities must be considered for disaster preparation. Vertical elevation was highly recommended for water, sewage, electricity, communication, and health services infrastructures.

Moore et al. [58] investigated erosion and flood risks due to SLR effects, such as storms and tsunamis, on the coastline of California. The researchers used Digital Elevation Models (DEM) on maps with GIS software in the analysis. The SLR scenario was selected by assuming a medium rate of increase in greenhouse gas emissions, which defined the rise of sea-level as 1.4m for 2100. The main conclusion was that the major infrastructures on the shoreline of California are at high risk for SLR.

Zhang et al. [59] investigated the inundation of the Florida Keys for incremental SLR scenarios with the digital elevation model for geographical maps. The Florida Keys is a series of lowland islands between the Atlantic Ocean and the Mexican Gulf. The research predicted an inundation of 70% of the whole land area for 0.6m SLR with a minimal amount of real property damage. A 1.5m increase in SLR was estimated to inundate over 90% of the total island area and the conclusion was that the region would be completely inundated by a 1.8m or greater increase in SLR.

Light detection and ranging (lidar) is a system that can produce high-quality topography maps. These maps are very helpful for the prediction of inundation in coastal regions due to SLR. The prediction could be useful in the management policy of coastal lines. Gesch [60] studied the inundation of the coastal region of North Carolina by lidar maps, concluding that the results of this method are more accurate than the previously used methods for this purpose. Wdowinski et al. [61] analyzed historical maps of Miami Beach, Florida for assessment of increasing flood risk. The frequency of flooding in the area was considerably increased from 2006 due to an increase in rain and a decrease in the drainage of coastal soils. The researchers recommended that the management of flood risk should be considered a local SLR effect.

Doughty et al. [62] developed a rule-based model that considered the local parameters on the impacts of SLR. The proposed model combined the effects of SLR and dynamic effects in the mouth of coves which could cause accumulation of water. Although California coasts were the chosen location of the case study, the authors highlighted that the model could be applied to study SLR effects on other coastal regions with localized conditions. Han, Jeanne, Fred, and Richard [63] studied the effects of earthquakes and ground motion on SLR rates in the Samoan islands, which experienced an extreme earthquake with a magnitude equal to 8.1 M_w in 2009. They used a monthly time series of spherical harmonic coefficients (GRACE) and GPS data to define the change in ground motion acceleration, finding that the ground motion acceleration is greater than the predictions and the motion could cause SLR of about five times the current global rate. Subsequently, extreme flooding and tsunamis could occur due to the increased SLR rate in the region.

3.7.2. Adaption and Management Options

Anderson et al. [64] developed the Synthesis and Assessment Product (SAP), which examines different factors of SLR. The SAP explains the SLR effects on the environment, wetlands, society, adaptations, and decisions. Although the mid-Atlantic coastal zone was selected as a case study, the results of SAP could be generalized for other U.S. regions. The SAP could support decision making for protection or adaptation to SLR effects on coastal zones. According to predictions for SLR magnitude, three scenarios were selected and the potential response of the studied zone was defined, as shown in Figure 11.

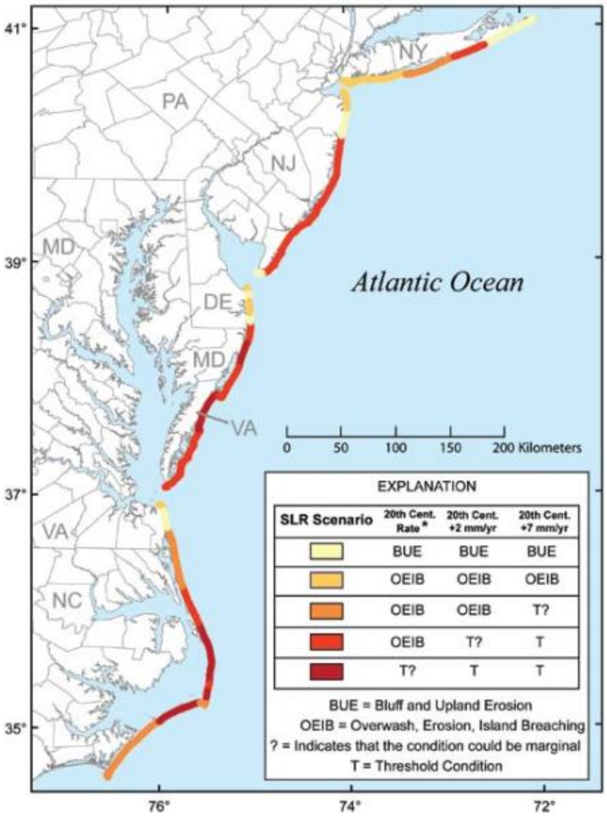


Figure 11. Coastal zone was studied by Anderson et al. [64]

Johnston, Slovinsky, and Yates [6] studied the vulnerability of infrastructures on the coastline of Maine under flooding conditions using GIS mapping data and analysis techniques. Their proposed method requires finite data and can be applied to other infrastructures. The resulting data implied that high traffic roads with discharge paths are at the highest risk in the studied region. Solutions that were suggested for reducing vulnerability of the infrastructure included location-specific, systemic, and strategic solutions. These solutions include structural and nonstructural methods, systemic improvements such as using more resilience materials for piping, and retreating methods in areas with high risk.

Rosenzweig et al. [65] explained the method and conformity tools which were suggested by the New York City Panel on Climate Change (NPCC) for infrastructures located near the coastline. Since the rate of climate change increased in 2018, the risk management programs should be updated. Figure 12 shows the risk management method that was proposed by NPCC (Flexible Adaption Pathway). The purpose of this method is to understand the responses of climate change over time. The NPCC has suggested an adaption method for shoreline infrastructures in eight steps, as shown in Figure 13.

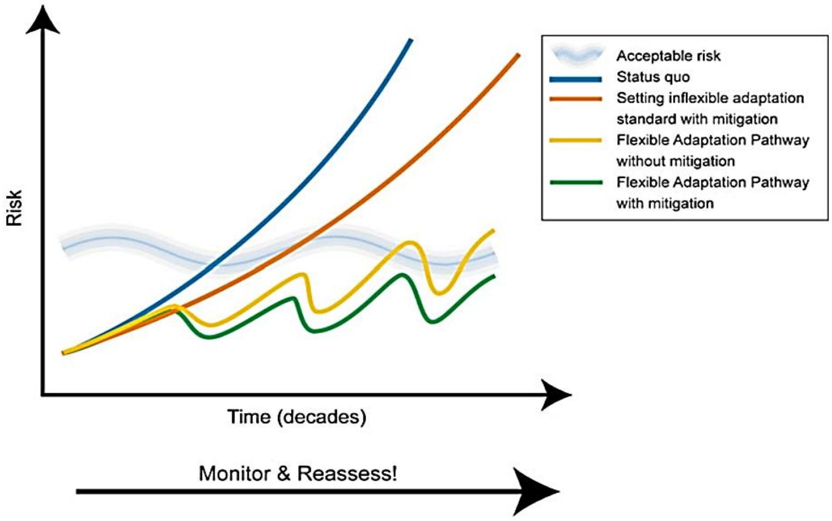


Figure 12. Flexible Pathway [65]

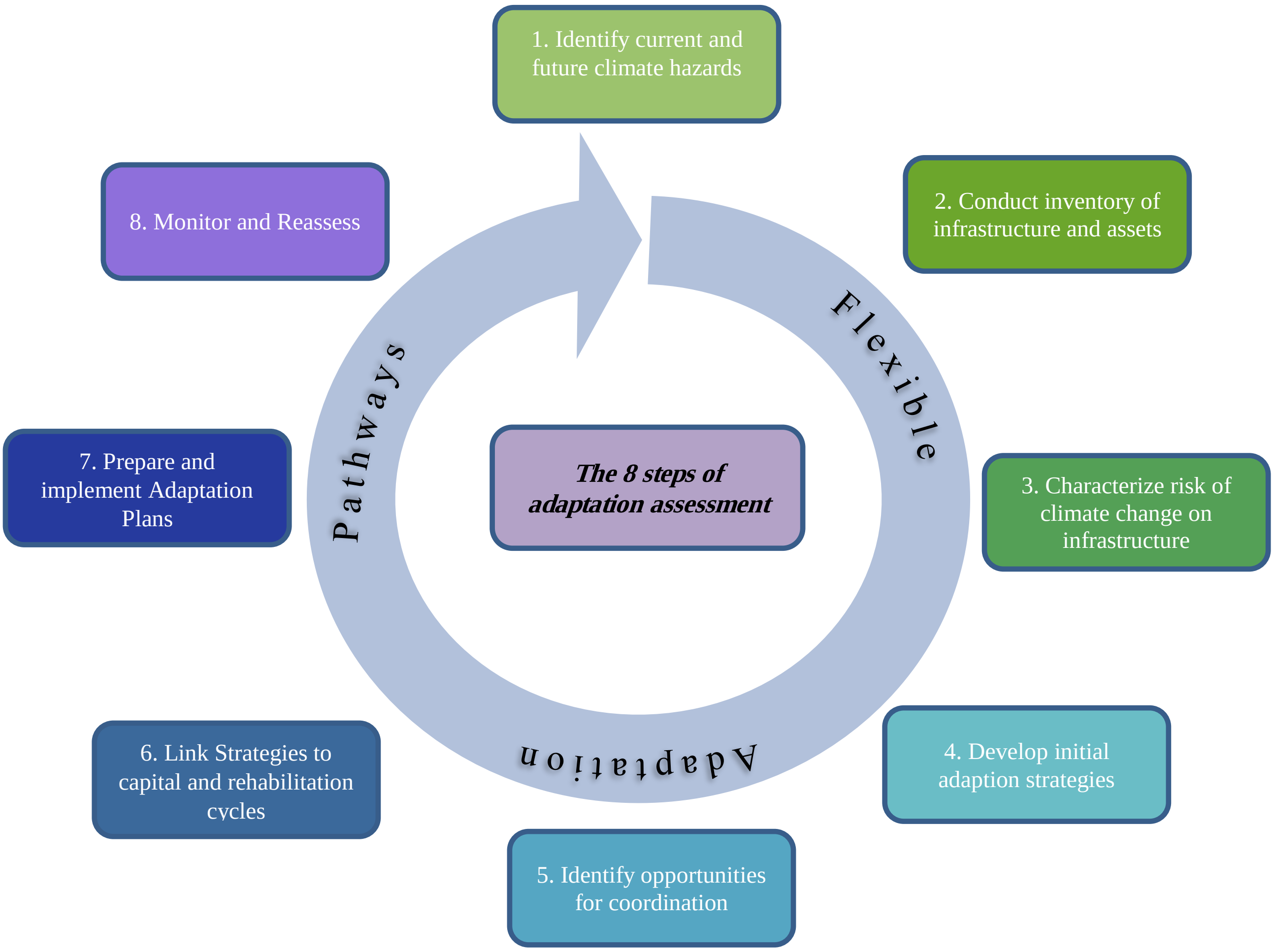


Figure 13. Eight steps of adaption processes of infrastructures under sea-level rise [65]

Pinto et al. (2018) [66] studied the obstacles for adaptation options in San Francisco Bay. The study utilized a connective method that incorporated interviews with stakeholders, analysis of instruments, and case study. The interviews with stakeholders focused on the effects of SLR on their institutions and future jurisdictional problems. Suggestions from stakeholders were considered to determine a framework. The researchers concluded that adaptations require cooperation between local and state governments, emphasizing policy efforts and collaborative actions.

Effects of SLR on Africa

The coasts of Africa and particularly Egyptian coasts, are predicted to be most populated second to those of Asia in the near future. The lowland region of the Nile delta contains agricultural areas. Refaat and Eldeberky [67] assessed the land area of the Nile delta in Egypt vulnerable to inundation due to SLR with Digital Elevation Models (DEM). The rate of subsidence for the studied area was approximated to 0.5cm/year. Adaptation options can be enacted to protect agricultural and residential areas with associated infrastructures from inundation.

Seawalls are constructed parallel to the shorelines with different materials such as stone, reinforced concrete, and steel. Stone seawalls are usually made with a slope that requires large stones. Moreover, the size and weights of the stones have a proportional relationship with the height of waves and depth of water. Abozaid et al. [68] proposed a novel seawall to protect the coastline of Egypt from erosion caused by SLR. The suggested seawall is composed of a vertical steel sheet facing the sea with a vertical constructed stone wall behind. The distance between the two aforementioned walls would be filled with stones.

3.8. Rest of the World

Passos et al. [64] investigated the effect of SLR on increasing erosion and flooding probability in the coastal zone of Mangaratiba located in Rio de Janeiro, Brazil. A digital mapping method proposed by Zhang et al. [59] was applied to predict the flood risk for different areas of the coast. The SLR was assumed to equal 2.15m in the simulation. The study concluded that floods could destroy a large area of the studied zone. Table 3 shows the different studied coastal regions which were reviewed in this section.

Table 3. List of reviewed case studies

Authors (Year)	Location of the Case study
Neumann et al. (2015)	UN countries and Taiwan
Abdel et al. (2011)	Southeast of Queensland, Australia
Few et al. (2007)	Christchurch Bay, UK
Anderson et al. (2009)	Mid-Atlantic region
Turbott and Stewart (2006)	New Zealand
London et al. (2009)	California, USA
Heberger et al. (2011)	California, USA
Pernetta(1992)	Maldives
Mimura (1999)	Island countries of South Pacific
Pethick (2001)	the east coast of Britain
STERR (2008)	Coastal Zone of Germany
Rosenzweig et al. (2011)	New York, USA
Lee (2014)	Mokpo, Korea
Johnston (2014)	Maine, USA
Devoy (2008)	Ireland
Neumann et al. (2015)	Red river Delta, Vietnam
Jianhui et al. (2011)	Taiwan Strait, Western coast
Abozaid et al. (2008)	Egypt
Passos et al. (2018)	Mangaratiba, Brazil
Zhang et al. (2011)	Florida Key, USA
Refaat and Eldeberky (2016)	Mediterranean Coast, Egypt
Mohd et al. (2018)	Pahang, Malaysia
Gesch (2009)	South Carolina, USA
Sahin and Mohamed (2013)	Gold Coast, Australia
Wdowinski et al. (2016)	Miami, USA

Griffiths et al. (2015)	Ningbo Municipality, China
Pinto et al. (2018)	San Francisco, USA
Xiao et al. (2018)	East-Central Florida, USA
Eriksson et al. (2017)	Island of Oland, Sweden
Vu et al. (2018)	Mekong Delta, Vietnam
Chun et al. (2018)	Gunsan tide, South Korea
Walsh and Miskewitz (2013)	Meadowland in New Jersey, USA
Dissanayake et al. (2012)	Amerland, Netherland
Rotzoll and Fletcher (2012)	Honolulu, Hawaii, USA
Hummel et al. (2018)	San Francisco Bay, USA
Davies et al. (2008)	Heisenberg, Sweden
Buzzanga (2017)	Southeastern Virginia, USA

4. Conclusions

The unprecedented increasing temperatures of the atmosphere due to greenhouse gas emissions is resulting in melting glaciers and expansion of water volume, consequently causing rising levels of oceans and seas. Multi-dimensional models accounting for local parameters to predict SLR effects on coastal lands and infrastructures are essential for risk assessment and planning appropriate actions. Investigations are much needed to understand SLR effects and improve planning and adaptation options. Threats to coastal regions include submergence of infrastructures and intrusion of saltwater into freshwater and groundwater. Damage to critical infrastructures would have serious consequences on social and economic levels. SLR will disrupt the serviceability of lifelines and drastically affect lives without effective planning and action. Collaborative efforts are crucial for addressing the interdisciplinary issues presented by SLR. Research is needed to perform comprehensive assessments of vulnerabilities, in addition to designing new structures and modifying existing structures for increased resilience. Governments and authoritative agencies have the responsibility to consider vulnerabilities of infrastructures, increase resiliency of infrastructures, and protect populations. Governments should invest in infrastructures, plan adaptive measures, and enact policies for responsible land use and development. Adaptation strategies for coastal management can be categorized into four main strategies: protection, accommodation, retreat, and inaction. All of the methods have their own risks and costs which must be analyzed; cost analysis assessments are necessary to determine the most effective and viable solutions for a specific area. Mitigation and adaptation actions are both important and must to be accounted for in governmental budgets. Industrial countries have a responsibility to reduce greenhouse gas emissions, implement adaptation strategies, and to help countries with weaker economies affected by SLR. This meta-analysis indicates that hybrid adaptation methods may be the most effective approach [69]. A hybrid method of adaptation could be any combination of pink (regulations, policy, and code), gray (structural), and green approaches. Various combinations of these adaptations should be evaluated for different sea-level rise scenarios in separate regions to hypothesize the most effective adaptations for a distinct region. Scenario analysis of various adaptations may indicate specific disruption patterns and prompt associated adaptation approaches. Table 4 provides a summary of aforementioned adaptations.

Table 4. Summary of adaptations, their application and consequences

Adaptation to SLR	Applicable	Protection method	Adaptation Cons	Recommendation for Cons	Examples	Features
Seawalls and Bulkheads	Urban area	Wave energy interception	Base erosion Undermined it	Placing rubble at the toe of the wall/ A soft approach like dune restoration and beach nourishment	-	Along with the coast/ need to be strengthened, elevate repeatedly
Groins	Beach	Intercept littoral sand moved	A little beach erosion	Soft approaches like dune restoration and beach nourishment	Westhampton Beach	Perpendicular and series/ strengthen, elevate repeatedly, sand replenishment in beach
Jetties	Inlets / harbors	Stabilize inlets / protect harbors	Beach erosion	Soft approaches like dune restoration and beach nourishment	-	Perpendicular and series/ strengthen, elevate repeatedly, sand replenishment in beach
Dune restoration	Beside hard protection or lonely In coastal area	Defense line against wave attack	Destroyed by housing construction/ Sand mining	Frequently replaced by artificial dunes	MEC region (Northeastern of US)	Soft Approach

Beach nourishment	Beside hard protection or lonely in the coastal area	Reduce erosion of hard protection	-	-	South shore of Long Island, NY, US	Soft Approach
Beach restoration	Erosion	Placing sand repeatedly	The large volume of sand	Reevaluate adequacy of onshore/offshore sand resources	Long Island, NY, and New Jersey, US	Soft Approach
Retreat or Pulling back from the shore (relocate)	Low population densities or land values/High-risk areas subject to repeated storm damage	Gradual or sudden abandonment following a catastrophic storm	Financial loose	Compensate owner with the governmental assistantship	Upton-Jones Amendment, 1987	-
Permit for new construction	Seaport	Landward elimination (30 years for small houses – 60 years for large building).	-	-	-	An appropriate method for future urban planning
Rolling easement Concept by human activity	At-risk areas	Prohibit hard structures like bulkheads which interfere with shoreline movement/state could acquire private land (acquisition programs).	Financial loose for owner	Compensate owner with the governmental assistantship	Florida, Maryland, New Jersey in the US	Some states currently have this type of program
Notification of disclosure of potential hazards	Private building	Notification of disclosure of potential coastal hazards before purchase	Reducing assets value and increase the rate of insurance	-	Massachusetts, South Carolina, and Texas	Some states currently have this type of program

5. Acknowledgements

The authors would like to thank Dr. Nipesh Pradhananga for his support.

6. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Poh. (2014) And Low-Lying Areas Coordinating Lead Authors : Lead Authors : Contributing Authors : Review Editors : 361–409.

[2] Nazarnia, Hadi, Hadi Sarmasti, and W. Olivia Wills. "Application of household disruption data to delineate critical infrastructure resilience characteristics in the aftermath of disaster: A case study of Bhaktapur, Nepal." Safety science 121 (2020): 573-579. https://doi.org/10.1016/j.ssci.2019.02.014.

[3] Res, Clim, Bubu P. Jallow, Sekou Toure, Malang M. K. Barrow, and Assa Achy Mathieu. (1999) "Jallow_etal_1999." 12:129–36.

[4] Neumann, Barbara, Athanasios T. Vafeidis, Juliane Zimmermann, and Robert J. Nicholls. "Future Coastal Population Growth and Exposure to Sea-Level Rise and Coastal Flooding - A Global Assessment." Edited by Lalit Kumar. PLOS ONE 10, no. 3 (March 11, 2015): e0118571. doi:10.1371/journal.pone.0118571.

[5] Ayyub, Bilal M., Haralamb G. Braileanu, and Naeem Qureshi. "Prediction and Impact of Sea Level Rise on Properties and Infrastructure of Washington, DC." Risk Analysis 32, no. 11 (October 28, 2011): 1901–1918. doi:10.1111/j.1539-6924.2011.01710.x.

[6] Johnston, A., P. Slovinsky, and K.L. Yates. "Assessing the Vulnerability of Coastal Infrastructure to Sea Level Rise Using Multi-Criteria Analysis in Scarborough, Maine (USA)." Ocean & Coastal Management 95 (July 2014): 176–188. doi:10.1016/j.ocecoaman.2014.04.016.

[7] Joyce, Justin, Ni-Bin Chang, Rahim Harji, Thomas Ruppert, and Sanaz Imen. "Developing a Multi-Scale Modeling System for Resilience Assessment of Green-Grey Drainage Infrastructures Under Climate Change and Sea Level Rise Impact." Environmental Modelling & Software 90 (April 2017): 1–26. doi:10.1016/j.envsoft.2016.11.026.

[8] Wang, Ruo-Qian, Mark T. Stacey, Liv Muir Meltzner Herdman, Patrick L. Barnard, and Li Erikson. "The Influence of Sea Level Rise on the Regional Interdependence of Coastal Infrastructure." Earth's Future 6, no. 5 (May 2018): 677–688. doi:10.1002/2017ef000742.

[9] Fletcher, Charles H., Patrick L. Barnard, Curt D. Storlazzi, Li Erikson, Sean Vitousek, and Neil Frazer. (2017) Doubling of Coastal Flooding Frequency within Decades Due to Sea-Level Rise. Scientific Reports 7(1):1–9.

[10] Crooks, Stephen. "The Effect of Sea-Level Rise on Coastal Geomorphology." Ibis 146 (September 23, 2004): 18–20. doi:10.1111/j.1474-919x.2004.00323.x.

[11] Schwartz, Maurice L. "The Bruun Theory of Sea-Level Rise as a Cause of Shore Erosion." The Journal of Geology 75, no. 1 (January 1967): 76–92. doi:10.1086/627232.

[12] Flood, Jefferson F., and Lawrence B. Cahoon. "Risks to Coastal Wastewater Collection Systems from Sea-Level Rise and Climate Change." Journal of Coastal Research 274 (July 2011): 652–660. doi:10.2112/jcoastres-d-10-00129.1.

[13] Abdoulhalik, Antoifi, and Ashraf A. Ahmed. "Transience of Seawater Intrusion and Retreat in Response to Incremental Water-Level Variations." Hydrological Processes 32, no. 17 (July 23, 2018): 2721–2733. doi:10.1002/hyp.13214.

[14] Xiao, Han, Dingbao Wang, Stephen C. Medeiros, Scott C. Hagen, and Carlton R. Hall. "Assessing Sea-Level Rise Impact on Saltwater Intrusion into the Root Zone of a Geo-Typical Area in Coastal East-Central Florida." Science of The Total Environment 630 (July 2018): 211–221. doi:10.1016/j.scitotenv.2018.02.184.

[15] Shi, Wenlong, Chunhui Lu, Yu Ye, Jichun Wu, Ling Li, and Jian Luo. "Assessment of the Impact of Sea-Level Rise on Steady-State Seawater Intrusion in a Layered Coastal Aquifer." Journal of Hydrology 563 (August 2018): 851–862. doi:10.1016/j.jhydrol.2018.06.046.

[16] Https://www.businessinsider.com/miami-floods-sea-level-rise-solutions-2018-4. (2020) Miami Is Racing against Time to Keep up with Sea-Level Rise, Retrived Feb 01, 2020.

[17] Titus, Jim. "Does sea level rise matter to transportation along the Atlantic Coast?." The potential impacts of climate change on transportation 135 (2002).

[18] Titus, James G., and James E. Neumann. "Implications for decisions." Coastal Elevations and Sensitivity to Sea-level Rise: A Focus on the Mid-Atlantic Region 4 (2009): 141-156.

[19] Hummel, Michelle A., Matthew S. Berry, and Mark T. Stacey. "Sea Level Rise Impacts on Wastewater Treatment Systems Along the U.S. Coasts." Earth's Future 6, no. 4 (April 2018): 622–633. doi:10.1002/2017ef000805.

[20] Koetse, Mark J., and Piet Rietveld. "The Impact of Climate Change and Weather on Transport: An Overview of Empirical Findings." Transportation Research Part D: Transport and Environment 14, no. 3 (May 2009): 205–221. doi:10.1016/j.trd.2008.12.004.

[21] Dawson, David, Jon Shaw, and W. Roland Gehrels. "Sea-Level Rise Impacts on Transport Infrastructure: The Notorious Case of the Coastal Railway Line at Dawlish, England." Journal of Transport Geography 51 (February 2016): 97–109. doi:10.1016/j.jtrangeo.2015.11.009.

[22] Jaroszweski, David, Elizabeth Hooper, and Lee Chapman. "The Impact of Climate Change on Urban Transport Resilience in a Changing World." Progress in Physical Geography: Earth and Environment 38, no. 4 (August 2014): 448–463. doi:10.1177/0309133314538741.

[23] Banister, David. "Cities, Mobility and Climate Change." Journal of Transport Geography 19, no. 6 (November 2011): 1538–1546. doi:10.1016/j.jtrangeo.2011.03.009.

[24] Brown, Sally, Susan Hanson, and Robert J. Nicholls. "Implications of Sea-Level Rise and Extreme Events Around Europe: a Review of Coastal Energy Infrastructure." Climatic Change 122, no. 1–2 (November 19, 2013): 81–95. doi:10.1007/s10584-013-0996-9.

[25] Rotzoll, Kolja, and Charles H. Fletcher. "Assessment of Groundwater Inundation as a Consequence of Sea-Level Rise." Nature Climate Change 3, no. 5 (November 11, 2012): 477–481. doi:10.1038/nclimate1725.

[26] Titus, James G., and K. Eric Anderson. Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic region. Vol. 4. Climate Change Science Program, 2009.

[27] Suh, Jonghae, Alain Tcheukam Siwe, and Samer Michel Madanat. "Transportation Infrastructure Protection Planning Against Sea Level Rise: Analysis Using Operational Landscape Units." Journal of Infrastructure Systems 25, no. 3 (September 2019): 04019024. doi:10.1061/(asce)is.1943-555x.0000506.

[28] Council, US Ocean Protection. "State of California sea-level rise guidance document." (2013).

[29] Dismukes, David E., and Siddhartha Narra. "Sea-Level Rise and Coastal Inundation: A Case Study of the Gulf Coast Energy Infrastructure." Natural Resources 09, no. 04 (2018): 150–174. doi:10.4236/nr.2018.94010.

[30] Jenkins, Lisa Martine, Robert Alvarez, and Sarah Marie Jordaan. "Unmanaged Climate Risks to Spent Fuel from U.S. Nuclear Power Plants: The Case of Sea-Level Rise." Energy Policy 137 (February 2020): 111106. doi:10.1016/j.enpol.2019.111106.

[31] Jallow, BP, MKA Barrow, and SP Leatherman. "Vulnerability of the Coastal Zone of The Gambia to Sea Level Rise and Development of Response Strategies and Adaptation Options." Climate Research 6 (1996): 165–177. doi:10.3354/cr006165.

[32] Pernetta, John C. "Impacts of Climate Change and Sea-Level Rise on Small Island States." Global Environmental Change 2, no. 1 (March 1992): 19–31. doi:10.1016/0959-3780(92)90033-4.

[33] Awang, N. A., M. R. Abdul Hamid, F. A. Mohd, A. H. Abd Razak, N. A. Abd Rahim, R. A. Begum, O. A. Karim, and K. N. bAbdul Maulud. (2018) Assessment of Coastal Inundation of Low Lying Areas Due to Sea Level Rise. IOP Conference Series: Earthand Environmental Science 169:012046.

[34] DHI (2017) MIKE 21 & MIKE 3 FLOW MODEL FM Hydrodynamic Module Short Description. Dismukes D and Siddhartha N. (2018) Sea-Level Rise and Coastal Inundation: A Case Study of the Gulf Coast Energy Infrastructure. Natural Resources 09(04):150–74.

[35] Ehsan, Sofia, Rawshan Ara Begum, Nor Ghani Md Nor, and Khairul Nizam Abdul Maulud. "Current and Potential Impacts of Sea Level Rise in the Coastal Areas of Malaysia." IOP Conference Series: Earth and Environmental Science 228 (February 15, 2019): 012023. doi:10.1088/1755-1315/228/1/012023.

[36] Mimura, N. "Vulnerability of Island Countries in the South Pacific to Sea Level Rise and Climate Change." Climate Research 12 (1999): 137–143. doi:10.3354/cr012137.

[37] Liu, Jianhui, Feng Cai, Hongshuai Qi, Gang Lei, and Lihua Cao. "Coastal Erosion Along the West Coast of the Taiwan Strait and It's Influencing Factors." Journal of Ocean University of China 10, no. 1 (January 26, 2011): 23–34. doi:10.1007/s11802-011-1745-1.

[38] Griffiths, James Andrew, Fangfang Zhu, Faith Ka Shun Chan, and David Laurence Higgitt. "Modelling the Impact of Sea-Level Rise on Urban Flood Probability in SE China." Geoscience Frontiers 10, no. 2 (March 2019): 363–372. doi:10.1016/j.gsf.2018.02.012.

[39] Chun, Jong, Changmook Lim, Daeha Kim, and Jin Kim. "Assessing Impacts of Climate Change and Sea-Level Rise on Seawater Intrusion in a Coastal Aquifer." Water 10, no. 4 (March 22, 2018): 357. doi:10.3390/w10040357.

[40] Vu, D. T., T. Yamada, and H. Ishidaira. "Assessing the Impact of Sea Level Rise Due to Climate Change on Seawater Intrusion in Mekong Delta, Vietnam." Water Science and Technology 77, no. 6 (January 31, 2018): 1632–1639. doi:10.2166/wst.2018.038.

[41] Klein, Richard JT, Robert J. Nicholls, Sachooda Ragoonaden, Michele Capobianco, James Aston, and Earle N. Buckley. "Technological options for adaptation to climate change in coastal zones." Journal of Coastal Research (2001): 531-543.

[42] Few, Roger, Katrina Brown, and Emma L. Tompkins. "Climate change and coastal management decisions: insights from Christchurch Bay, UK." Coastal Management 35, no. 2-3 (2007): 255-270.

[43] Hill, Kristina. "Coastal Infrastructure: a Typology for the Next Century of Adaptation to Sea- level Rise." Frontiers in Ecologyand the Environment 13, no. 9 (November 2015): 468–476. doi:10.1890/150088.

[44] Lee, Yumi. "Coastal Planning Strategies for Adaptation to Sea Level Rise: A Case Study of Mokpo, Korea." Journal of Building Construction and Planning Research 02, no. 01 (2014): 74–81. doi:10.4236/jbcpr.2014.21007.

[45] Norman, Barbara. "Principles for an Intergovernmental Agreement for Coastal Planning and Climate Change in Australia." Habitat International 33, no. 3 (July 2009): 293–299. doi:10.1016/j.habitatint.2008.10.002.

[46] Turbott, Christopher and Andrew Stewart (2006) Managed Retreat from Coastal Hazards : Options for Implementation. Environment (April):97.

[47] Abel, Nick, Russell Gorddard, Ben Harman, Anne Leitch, Jennifer Langridge, Anthony Ryan, and Sonja Heyenga. "Sea Level Rise, Coastal Development and Planned Retreat: Analytical Framework, Governance Principles and an Australian Case Study." Environmental Science & Policy 14, no. 3 (May 2011): 279–288. doi:10.1016/j.envsci.2010.12.002.

[48] Sahin, Oz, and Sherif Mohamed. "A Spatial Temporal Decision Framework for Adaptation to Sea Level Rise." Environmental Modelling & Software 46 (August 2013): 129–141. doi:10.1016/j.envsoft.2013.03.004.

[49] Dissanayake, D. M. P. K., R. Ranasinghe, and J. A. Roelvink. "The Morphological Response of Large Tidal Inlet/basin Systems to Relative Sea Level Rise." Climatic Change 113, no. 2 (April 21, 2012): 253–276. doi:10.1007/s10584-012-0402-z.

[50] Cooper, J. Andrew G., and Orrin H. Pilkey. "Sea-Level Rise and Shoreline Retreat: Time to Abandon the Bruun Rule." Global and Planetary Change 43, no. 3–4 (November 2004): 157–171. doi:10.1016/j.gloplacha.2004.07.001.

[51] Semadeni-Davies, Annette, Claes Hernebring, Gilbert Svensson, and Lars-Göran Gustafsson. "The Impacts of Climate Change and Urbanisation on Drainage in Helsingborg, Sweden: Combined Sewer System." Journal of Hydrology 350, no. 1–2 (February 2008): 100–113. doi:10.1016/j.jhydrol.2007.05.028.

[52] Walsh, Sean, and Robert Miskewitz. "Impact of Sea Level Rise on Tide Gate Function." Journal of Environmental Science and Health, Part A 48, no. 4 (March 2013): 453–463. doi:10.1080/10934529.2013.729924.

[53] Habel, Shellie, Charles H. Fletcher, Kolja Rotzoll, and Aly I. El-Kadi. "Development of a model to simulate groundwater inundation induced by sea-level rise and high tides in Honolulu, Hawaii." Water research 114 (2017): 122-134. doi: 10.1016/j.watres.2017.02.035

[54] Buzzanga, A. (2017) Precipitation and Sea Level Rise Impacts on Groundwater Levels in Virginia Beach , Virginia.

[55] USGS Groundwater Information (2005) MODFLOW and Related Programs. U.S. Department of the Interior & U.S. Geological Survey U.S. Geological Survey 2005.

[56] Flood, Jefferson F., and Lawrence B. Cahoon. "Risks to Coastal Wastewater Collection Systems from Sea-Level Rise and Climate Change." Journal of Coastal Research 274 (July 2011): 652–660. doi:10.2112/jcoastres-d-10-00129.1.

[57] Allen T, Crawford T, Montz B, Whitehead J, Lovelace S, Hanks A, Christensen A, and Kearney G. (2018) Linking Water Infrastructure , Public Health , and Sea Level Rise : Integrated Assessment of Flood Resilience in Coastal Cities.

[58] Heberger, Matthew, Heather Cooley, Pablo Herrera, Peter H. Gleick, and Eli Moore. "Potential Impacts of Increased Coastal Flooding in California Due to Sea-Level Rise." Climatic Change 109, no. S1 (November 24, 2011): 229–249. doi:10.1007/s10584-011-0308-1.

[59] Zhang, Keqi, John Dittmar, Michael Ross, and Chris Bergh. "Assessment of Sea Level Rise Impacts on Human Population and Real Property in the Florida Keys." Climatic Change 107, no. 1–2 (May 15, 2011): 129–146. doi:10.1007/s10584-011-0080-2.

[60] Gesch, Dean B. "Analysis of Lidar Elevation Data for Improved Identification and Delineation of Lands Vulnerable to Sea-Level Rise." Journal of Coastal Research 10053 (November 2009): 49–58. doi:10.2112/si53-006.1.

[61] Wdowinski, Shimon, Ronald Bray, Ben P. Kirtman, and Zhaohua Wu. "Increasing Flooding Hazard in Coastal Communities Due to Rising Sea Level: Case Study of Miami Beach, Florida." Ocean & Coastal Management 126 (June 2016): 1–8. doi:10.1016/j.ocecoaman.2016.03.002.

[62] Doughty, Cheryl L., Kyle C. Cavanaugh, Richard F. Ambrose, and Eric D. Stein. "Evaluating Regional Resiliency of Coastal Wetlands to Sea Level Rise through Hypsometry-based Modeling." Global Change Biology 25, no. 1 (October 30, 2018): 78–92. doi:10.1111/gcb.14429.

[63] Han, Shin-Chan, Jeanne Sauber, Fred Pollitz, and Richard Ray. "Sea Level Rise in the Samoan Islands Escalated by Viscoelastic Relaxation After the 2009 Samoa-Tonga Earthquake." Journal of Geophysical Research: Solid Earth 124, no. 4 (April 2019): 4142–4156. doi:10.1029/2018jb017110.

[64] Dos Santos Passos, Anderson, Fábio Ferreira Dias, Paulo Roberto Alves dos Santos, Sérgio Ricardo da Silveira Barros, Celia Regina de Gouveia Souza, Dandara Bernardino, Julia Caon Araujo, Ruan Vargas, and Camila Américo dos Santos. "Evaluation of the Effects of a Possible Sea-Level Rise in Mangaratiba - RJ." Journal of Coastal Conservation 23, no. 2 (September 29, 2018): 355–366. doi:10.1007/s11852-018-0665-2.

[65] Rosenzweig, Cynthia, William D. Solecki, Reginald Blake, Malcolm Bowman, Craig Faris, Vivien Gornitz, Radley Horton, et al. . "Developing Coastal Adaptation to Climate Change in the New York City Infrastructure-Shed: Process, Approach, Tools, and Strategies." Climatic Change 106, no. 1 (February 26, 2011): 93–127. doi:10.1007/s10584-010-0002-8.

[66] Pinto, Pedro J., G. Mathias Kondolf, and Pun Lok Raymond Wong. "Adapting to Sea Level Rise: Emerging Governance Issues in the San Francisco Bay Region." Environmental Science & Policy 90 (December 2018): 28–37. doi:10.1016/j.envsci.2018.09.015.

[67] Refaat, Mervat M., and Yasser Eldeberky. "Assessment of Coastal Inundation Due to Sea-Level Rise Along the Mediterranean Coast of Egypt." Marine Geodesy 39, no. 3–4 (May 13, 2016): 290–304. doi:10.1080/01490419.2016.1189471.

[68] Abozaid (2008) Using Porous Seawalls to Protect the Coasts against Sea Level Rise Due to Climatic Changes. Msc Thesies, Zagazig University.

[69] Nazarnia, Hadi, and Hadi Sarmasti. "Characterizing infrastructure resilience in disasters using dynamic network analysis of consumers' service disruption patterns." Civil Engineering Journal 4, no. 10 (2018): 2356-2372. doi:10.28991/cej-03091165.