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Review

Resilience of Infrastructure Systems to Sea-Level Rise in Coastal Areas: Impacts, Adaptation Measures, and Implementation Challenges

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Abstract: Expansive areas of low elevation in many densely populated coastal areas are at elevated risk of storm surges and flooding due to torrential precipitation, as a result of sea level rise. These phenomena could have catastrophic impacts on coastal communities and result in the destruction of critical infrastructure, disruption of economic activities and salt water contamination of the water supply. The objective of the study presented in this paper was to identify various impacts of sea level rise on civil infrastructures in coastal areas and examine the adaptation measures suggested in the existing literature. To this end, a systemic review of the existing literature was conducted in order to identify a repository of studies addressing sea level rise impacts and adaptation measures in the context of infrastructure systems. The study focused on three infrastructure sectors: water and wastewater, energy, and road transportation. The collected information was then analyzed in order to identify different categories of sea level rise impacts and corresponding adaptation measures. The findings of the study are threefold: (1) the major categories of sea level rise impacts on different infrastructure systems; (2) measures for protection, accommodation, and retreat in response to sea level rise impacts; and (3) challenges related to implementing adaptation measures.

Keywords: sea level rise; infrastructure systems; coastal areas; impacts; adaptation measures; implementation challenges; energy; water and wastewater; transportation

1. Introduction

Climate change is one of the major challenges of the 21st century. Sea-level rise is one of the most concerning and costly effects of climate change. Sea-level rise has been estimated to be on average +2.6 mm and +2.9 mm per year ±0.4 mm since 1993. Global average sea-levels could rise by as much as 6 feet by 2100 [1]. A rise of only 1.6 feet by 2070 puts 150 million people globally and $35 trillion assets at risk in 20 of the world's most vulnerable and fastest growing port cities [1].

In the United States, of the 25 most densely populated and rapidly growing U.S. counties, 23 are along a coast [2]. Low-lying coastal areas are particularly susceptible to storm surge and flooding from torrential precipitation, and the effects on communities can be catastrophic. In the future, such effects will be intensified by rising sea levels [3,4]. The evolving hazard profile of coastal communities due to sea level rise affects infrastructure systems in multiple ways [5–9]: (i) accelerated degradation of infrastructure networks due to chronic and acute weather impacts; (ii) increased exposure of infrastructure networks to disruptive events; and (iii) greater likelihood of cascading failures due to increased interdependencies between infrastructure networks. Resulting hazard event impacts may include failures or destruction of critical infrastructure, immobilization due to transportation system breakdown, blackouts due to power grid failures, and catastrophic saltwater contamination of water supplies. These failures in infrastructure systems may lead to prolonged disruption of economic activities and livelihoods in coastal communities. A 100-year storm surge, which is expected to begin occurring every 3–20 years, could cost billions of dollars in direct damages after 1 foot of sea-level rise [1]. Hence, with the aging of infrastructure systems and projected population growth in coastal urban areas [10], there is an urgent need to investigate adaptation pathways to mitigate the public safety and economic impacts of sea-level rise.

A critical aspect of mitigating the adverse impacts of sea-level rise on coastal urban areas is the adaptation of built infrastructure systems. Sea-level rise has a significant impact on the built infrastructure systems in coastal communities. The increase in precipitation as well as the frequency and magnitude of inland flooding expedites the erosion of roads and bridges and makes them more vulnerable to failures. Sea-level rise also affects water and wastewater infrastructure networks significantly. Salt water intrusion into groundwater aquifers is one of the major impacts of sea-level rise. Hence, saltwater intrusion could lead to significant disruptions in water supply networks. In addition, treatment plants are located in low-lying areas and exposed to flooding and storm surge events. For wastewater infrastructure, sea-level rise can lead to sewage backup due to the failure of septic tanks and conveyance pipes due to elevation of water tables. Also, wastewater network pump stations and treatment facilities are significantly exposed to flooding and storm surge risks.

Despite the urgency of this societal and environmental challenge, a better understanding of the impacts of sea-level rise on different built infrastructure systems and possible adaptation actions to mitigate these impacts in coastal areas are missing in the existing literature. To address this knowledge gap, the objective of the study presented in this paper was to identify sea-level rise impacts on coastal protection, transportation, water, wastewater, and energy infrastructures and investigate possible adaptation measures to mitigate sea-level rise impacts. Also, this study aimed to investigate the adaption implementation challenges for resilient built infrastructures in coastal areas. To this end, in this study, a comprehensive review of the existing literature related to sea-level rise impacts and adaptation measures was conducted. Information collected from the existing literature included studies in various countries such as The Netherlands, U.S., Australia, China, Israel, Egypt, and Bangladesh. The information was synthesized and analyzed to identify sea-level rise impacts and document adaptation actions and their implementation challenges for coastal protection, water, energy, and transportation infrastructure systems. For each infrastructure system, the impacts and adaptation measures are presented along with examples from different regions. Finally, the challenges related to the implementation of adaptation measures are discussed. In this study, we did not consider all infrastructure sectors and all climate change impacts. The focus of this study is on the analysis of the impacts of sea level rise on water, wastewater, energy, and transportation infrastructure systems.

2. Materials and Methods

To identify the impacts of sea level rise and adaptations in infrastructure systems, a systematic information collection related to articles and reports related to different geographic locations across the globe was conducted. First, more than one hundred scholarly articles, government reports, and non-governmental documents were identified through searching scholarly databases. The articles and reports published between 1980 and 2016 were included in a literature repository. These documents were initially reviewed to identify the ones with relevant information related to sea-level rise impacts and adaptation measures in the context of water, wastewater, energy and transportation infrastructure systems. Then, 47 articles and reports were compiled for further evaluation. These articles and reports were reviewed and coded to extract, synthesize, and analyze information related to sea level rise (SLR) impacts, adaptation measures, and implementation challenges related to water, wastewater, energy, and transportation infrastructure systems. Figure 1 summarizes the process for identification, coding, synthesis, and analysis of information. Figure 2 shows the research framework and information elements used for coding the collected information.

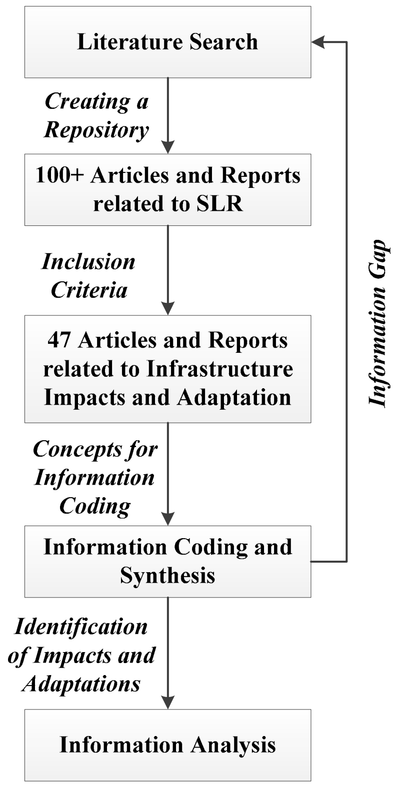

Figure 1. Information collection, synthesis, and analysis process.

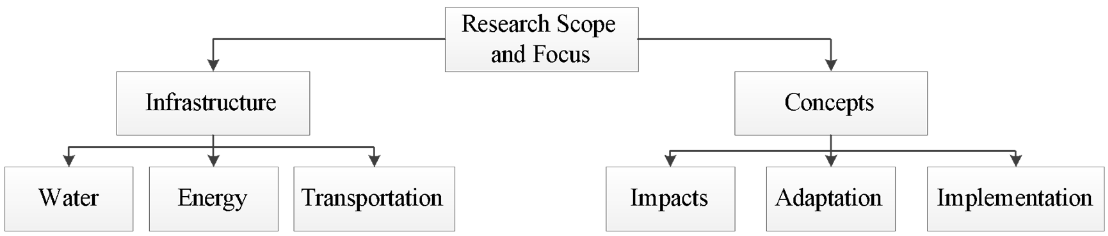

Figure 2. Research scope and focus.

These articles and reports were from different geographic locations. Figures 3 and 4 depict the distribution of the studies based on their geographic locations and show which infrastructure system was the focus of each research. Figure 3 shows that in the United States, the studies are concentrated in the coastal areas which are most threatened by sea level rise. Figure 4 shows that other countries are also concerned with sea level rise. Also, Figure 5 shows the number of articles per year included in the repository. As shown in Figure 5, there are more studies related to sea level rise and adaptation measures for water and wastewater infrastructure. Around 47% of the studies identified and reviewed were related to water and wastewater infrastructure, 23% for transportation, and 30% for energy infrastructure.

Each article/report had a different focus and evaluated different aspects of SLR impacts on different infrastructure systems. Throughout this systematic review, identification of SLR impacts and adaptation measures from different resource continued until additional review of documents did not lead to the identification of new information. Figure 6 shows the number of impacts identified for each infrastructure system. It is apparent that the most common impact is flooding and almost all articles address this issue. Figure 7 shows the number of adaptation measures identified for each impact in different infrastructure systems. It shows that the most common adaptation method is the construction of seawalls and tide gates.

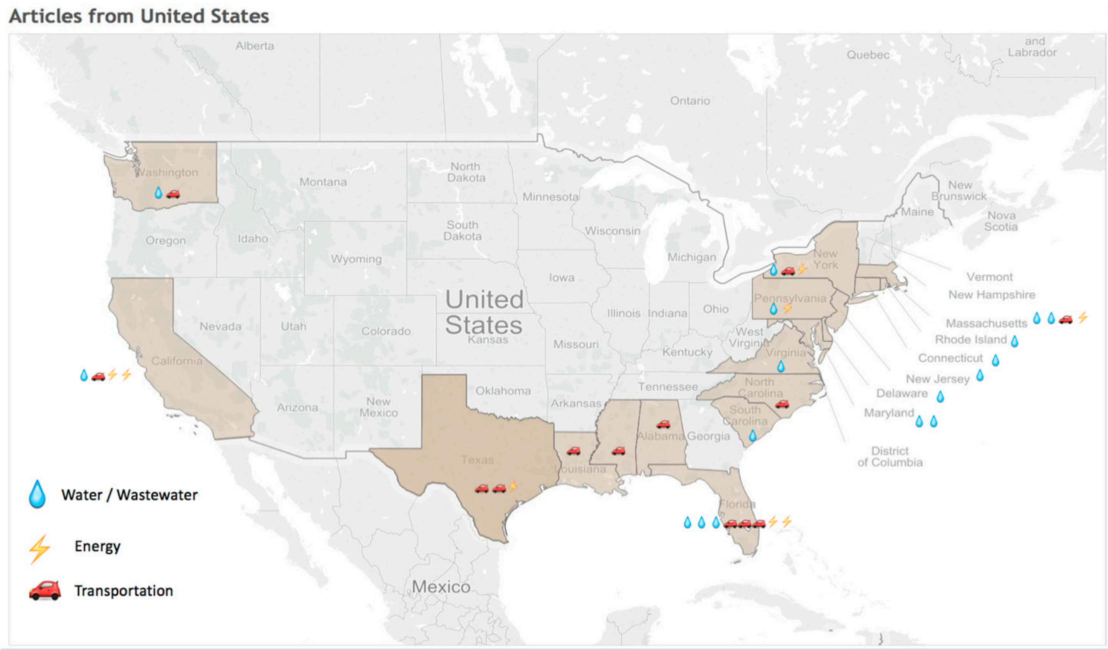

Figure 3. Distribution of studies in the United States.

Figure 4. Distribution of studies around the world.

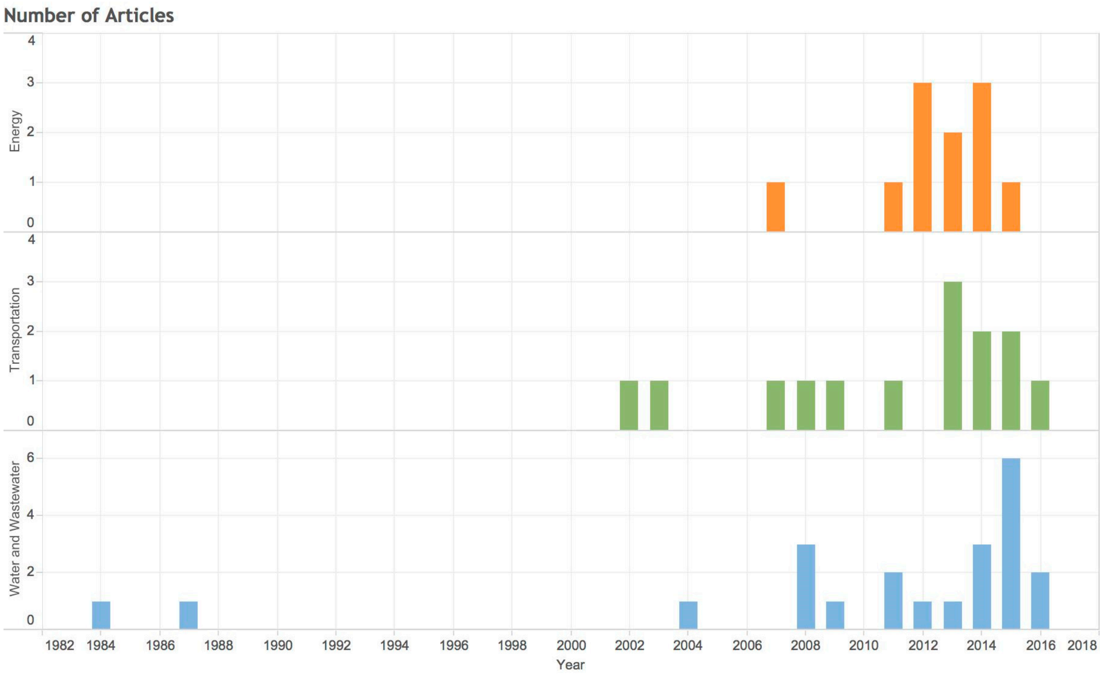

Figure 5. Number of articles per year included in the repository.

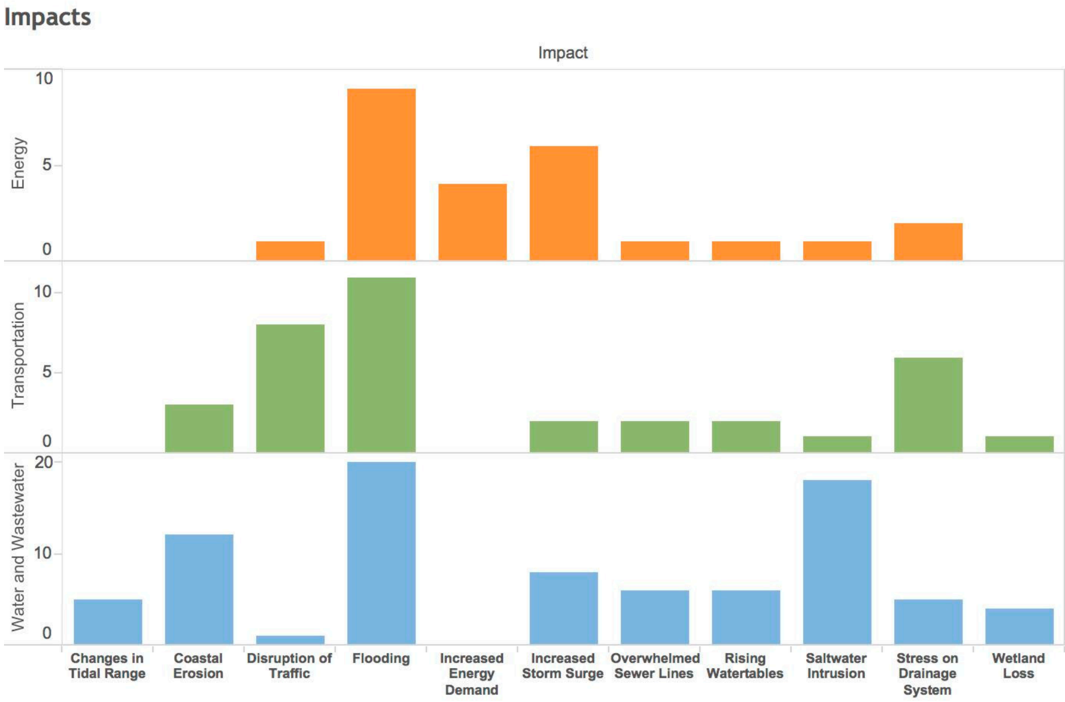

Figure 6. Number of impacts reported in the articles reviewed.

Figure 7. Number of adaptation measures reported in the articles reviewed.

3. Sea Level Rise Impacts on Coastal Areas

Sea level rise has four major impacts in coastal areas: (1) Coastal Flooding; (2) Coastal Erosion; (3) Exacerbated Land Subsidence; and (4) Saltwater Intrusion. While these impacts already exist in coastal regions, sea-level rise exacerbates their severity.

(1) Coastal Flooding: The primary consequence of SLR is an increase in the exposure of coastal communities to flooding. Recreational beach areas will decrease as more and more dry beach is submerged during tidal cycles. Some areas that are only submerged at high tide could be submerged for the whole day. Structures that are built on the water, like docks and piers, will be closer to the water, or possibly become submerged. Low-lying coastal areas are particularly susceptible to storm surge and flooding from torrential precipitation, and the community effects can be catastrophic. In the coming years, these effects will be intensified by rising sea levels [3,4]. Intense precipitation events alone already cause substantial flooding. The amount of rain falling in on the wettest day are expected to increase 10%–20% by 2100 [11] and sea level rise will lead to higher water tables and reduced soil storage capacity. As sea level rises and water tables approach the land surface, the frequency and severity of flooding induced by precipitation will increase. Hence, it no longer takes a strong storm to cause coastal flooding [10]. Even a small rise in sea level, as modeled by any of the International Panel on Climate Change (IPCC) scenarios, could have significant impacts on the coastal areas over the next 100 years. Coastal flooding that currently has an annual probability of occurrence of 1% will become more frequent. The change in the intensity of flooding may result in changes in exposures of flooded areas, the level of the base flood, and the amount of damage caused by flooding. Flooding occurs with high tides in many locations due to sea level rise, land subsidence, and the loss of natural barriers. For example, the City of Miami Beach in Florida and Charleston in South Carolina already experience periodic flooding during extreme high tides. Nuisance flooding occurs due to changes in tidal levels. According to the National Oceanic and Atmospheric Administration (2012) [10],

nuisance flooding has increased significantly in the U.S. coast since the 1960s. Nuisance flooding causes road closures and saltwater backup in storm drains and exposes infrastructure [10]. A large number of communities are already exposed to coastal flooding. As noted by [12], there are 136 major port cities with more than one million inhabitants each, 13 of which are among the top 20 most populated cities in the world. Nicholls (2008) [13] suggests that exposure to coastal flooding is expected to increase with growing populations and the increased economic relevance of coastal cities, particularly in developing countries. Also, a study [14] showed that nine counties in California, near the Pacific Ocean, are threatened due to sea level rise and their vulnerability will increase in the following decades.

(2) Coastal Erosion: There has been a direct relationship between sea-level rise and the reduction of coastal shorelines. Past studies have proved that as sea level rises, it creates substantial erosion of coastal beaches, rocks, and low-lying areas [15]. Rising sea level leads to the loss of land adjacent to the coast, reducing further up the shoreline. As coastal lines reduce due to the effects of sea level rise, many critical infrastructures, and buildings are left vulnerable. In particular, coastal erosion produces two major effects on coastal areas. First, infrastructure facilities and buildings are exposed to the displacement of foundation soils, and hence, structures are more prone to falling due to the inadequate support of the soil. Second, the exposure of underground utilities and assets may affect pipelines and equipment. In addition, coastal erosion changes the panoramic scene of beaches, and where coastal leisure has a significant impact on an area's economy, eroded beaches affect tourism and business that depend on the beaches. According to [16], with a significant rise in sea level, there will be an acceleration of beach erosion in areas already eroding and possibly a start of erosion in areas not previously subject to erosion. The main reason for the increase in erosion is that when the water level is high it allows the waves and the erosion process to act farther up on the beach profile, causing a readjustment and resulting in a net erosion of the beach. When sea level rises, the waves can get closer to the coast before breaking and cause further erosion. Also, when water bodies are deeper, there is a reduction in the refraction of waves, and therefore there is an increase in transport capacity along the coast. With the rise in sea level, changes may occur in the supply of sediment, reducing the transport of water from the rivers to the sea as the mouth is flooded. Many of the world's infrastructure facilities such as power generation facilities, refineries stations, water and wastewater treatment plants, and transportation networks are located along coastlines. As sea levels rise and coastlines erode, infrastructures are more exposed to the forces of nature and becoming structurally unstable. As the stability of adjacent coastal land diminishes due to eroding bases, infrastructure systems start displacing significantly to the point that they become hazards to users.

(3) Exacerbated Land Subsidence: Land subsidence contributes to relative sea level rise and the resulting impacts on coastal areas. Coastal areas lay on unconsolidated or poorly consolidated sediments whose thickness varies from almost zero along the hillside to thousands of meters under the continental shelf. For example, along the U.S. Atlantic shore, severe head reduction in unconsolidated materials can lead to compaction of the aquifer materials. This problem exists in various coastal regions across the globe. This compaction is referred to as land subsidence. Land subsidence is captured through repetitive leveling, and in some cases, via analysis of tide-gauge recorded data with eliminating effects of sea level changes. The most part of compaction is because of the slow drainage of water from clay sediments into intercalated sands. Some studies (e.g., [17]) show a constant ratio of subsidence and head reduction in the U.S. East Coast and areas with greater montmorillonite clay mineral. Land subsidence can increase flooding, alter wetland and coastal ecosystems, and damage infrastructure. One important contributor to land subsidence is ground water extraction. In most coastal cities, millions of gallons of water are extracted from groundwater which is a relatively inexpensive water source for industry and municipal usage. Land subsidence increases the risk of flooding in low-lying areas further from the coast. In addition, land subsidence may alter the topographic gradient

of coastal areas affecting the risk of flooding. Land subsidence can also cause damage to roads, underground utilities, and other infrastructure systems.

(4) Saltwater Intrusion: Saltwater intrusion can be described as a mass transport of saline water into aquifer zones that were previously occupied by freshwater. The rise of sea levels is likely to cause saltwater intrusion into coastal groundwater systems affecting not only the availability of drinking water supply, but also underground utilities that could be vulnerable to damage when in contact with the saltwater. The increase in salinity levels reduces water quality exceeding acceptable limits for potable uses. As the saltwater has a higher density, when the intrusion occurs there is a displacement of groundwater causing a rise in the water tables. This usually occurs in coastal and estuarine areas due to relative sea level rise or the reduced runoff and associated groundwater recharge. Reference [18] proposed a climate model that indicates that climate change during the next 50–100 years will decrease river discharges in some coastal waters and the salinity of coastal estuaries and wetlands is expected to increase causing a decrease in the amount of sediments and nutrients delivered to the coast. When stream flow decreases, salinity will tend to advance upstream, altering the zonation of animal and plant species and the availability of freshwater for human use.

The above-mentioned general sea level rise impacts lead to multiple specific impacts on infrastructure systems. In the following sections, the specific impacts of sea level rise as well as adaptation measures related to water, energy, and transportation infrastructures are discussed. Then, the implementation challenges for the discussed adaptation measures are discussed.

4. Water and Wastewater Infrastructure

4.1. SLR Impacts on Water and Wastewater Infrastructure

The sea level rise impacts lead to sector-specific effects for water and wastewater infrastructure. In this section, the impacts of sea level rise on water and wastewater infrastructure are summarized and suitable adaptation actions are discussed. The impacts of sea-level rise on water and wastewater infrastructure are fivefold: (1) Damages due to land subsidence; (2) Degradation of underground utility; (3) Saltwater intrusion into groundwater and estuaries; (4) Sewage overflow; (5) Inundation of low-lying treatment facilities.

(1) Damages due to land subsidence: Land subsidence is recognized as a chronic hazard affecting water and storm water systems. First, land subsidence changes the flow patterns and the runoff on the land surface, and thus affects urban stormwater collection systems. Therefore, in evaluation of storm water systems for future flood hazards, it is important to consider the temporal variations of the urban topography induced by land subsidence. Existing local topographic characteristics and subsequent relative land subsidence play an important role in either exacerbating or reducing water depth changes over time. In addition, areas with a significant difference in water depth tend to be associated with more intense rainfall [19]. Land subsidence can lead to moderate impacts on the spatiotemporal distribution of floods in urban areas with high density. A response to land subsidence involves routing dynamic stormwater through a changing landscape. Second, when sea level rises and land subsides, groundwater levels rise towards the land surface and can cause damage to some structures such as pipes, bridges, and buildings and to infrastructures that are not designed for elevated groundwater levels. This phenomenon increases the rate of corrosion in underground pipelines. In addition, storm and wastewater sewers become vulnerable because land subsidence can change the topographic gradient driving sewer flow and cause sewer overflow during flooding events [20,21].

(2) Degradation of underground utilities: With sea levels rising, groundwater levels rise during extreme tides affecting the buried utilities and structures interacting with the land soil. In coastal regions, storm water systems are designed for draining surface runoff to the ocean.

With rising groundwater levels, groundwater inundation prevents drainage and runoff infiltration. Since urban drainage systems have a certain design capacity, more frequent rainfalls and subsequent water run-off will threaten the ability of these systems to cope with the required discharge [22,23]. In addition, due to sea level rise and increasing aquifer salinity, subsurface structures, such as water and sewer pipes, will corrode at a faster rate [24]. A corroded pipe can cause wastewater, sometimes untreated, to be diverted into nearby fields or bodies of water [25]. In addition, groundwater inundation leads to groundwater elevation and exerts uplift forces on buried water infrastructure [26]. Furthermore, land subsidence causes pressures on buried pipelines and utilities and also changes their gradient driving sewer flow. The change of topological gradient causes sewer overflow during flooding events. This phenomenon leads to increased flooding and more frequent sewage discharge from combined sewer overflows [20].

(3) Saltwater intrusion into groundwater and estuaries: With a constant discharge rate from groundwater wells and after a certain rise in sea levels, saltwater will start to flow into the wells from the shores. Saltwater intrusion affects the salinity of groundwater requiring the treatment plants to conduct desalination. Saltwater intrusion causes serious challenges since more than 80% of water supply in coastal areas is provided by groundwater [25]. The intrusion of saltwater into groundwater systems changes the elevation of the freshwater–saltwater interface, and thus, affects coastal ecosystems such as marshes. Saltwater intrusion causes an increase in chloride concentration in the water and if ingested, could cause high blood pressure. Furthermore, the higher chloride concentration can cause corrosion of the pipes of the drinking water facility. In addition, according to [25], saltwater intrusion into water treatment plants could kill the bacteria used on the biological treatment of water.

(4) Sewage overflow: Sewage overflow happens when untreated sewage is released to the environment prior to reaching the treatment plant. While storm water drainage systems are designed for draining surface runoff, groundwater inundation caused by sea level rise reduces the drainage capacity of storm water systems, and thus, could affect drainage and runoff infiltration. For example, during Hurricane Sandy in 2012, sewage backup led to the overflow of 11 billion gallons of raw sewage into the streets, rivers, and coastal waters [27]. Sewage overflow has severe health and environmental consequences. In addition, during flooding situations, wastewater facilities can get overwhelmed by excess water. This causes sewer pipes to be overloaded, and as a result, the sewage backs up into homes or low-lying areas. This back-up in the sewer lines may become a breeding ground for bacteria such as *E. coli*. Also, when a wastewater facility is inundated, facility operators are forced to skip the treatment process and release the untreated water into nearby rivers or streams, which may be used as a source of drinking water [25].

(5) Inundation of low-lying treatment facilities: Wastewater facilities in coastal areas are constructed in low-lying areas in order to reduce the need for energy to pump the effluent into the receiving water as it can be piped by gravity. Hence, wastewater treatment plants in low-lying areas are susceptible to flooding or extreme high tides caused by sea level rise. With a higher groundwater level, wastewater infrastructure may overwhelm, interfering with its function and preventing access to critical roads. Many treatment plants typically discharge their wastewater through underwater pipes, which can cause flood from the inside as waters rise, long before the surface water levels overrun the outside of the structures. Thereby, treatment plants located at low elevation may be jeopardized and instead of saving energy, more pumps will be needed to keep them in service. Flooded wastewater facilities will suffer from structural damages. In addition to structural damages, inundation of treatment plants could cause damage to the electrical systems and affect the operation of plants. Also, many plants discharge their treated wastewater through underwater pipes, which can cause plants to flood from the inside as sea level rises [28]. Figure 8 shows the impacts on water, wastewater and stormwater systems.

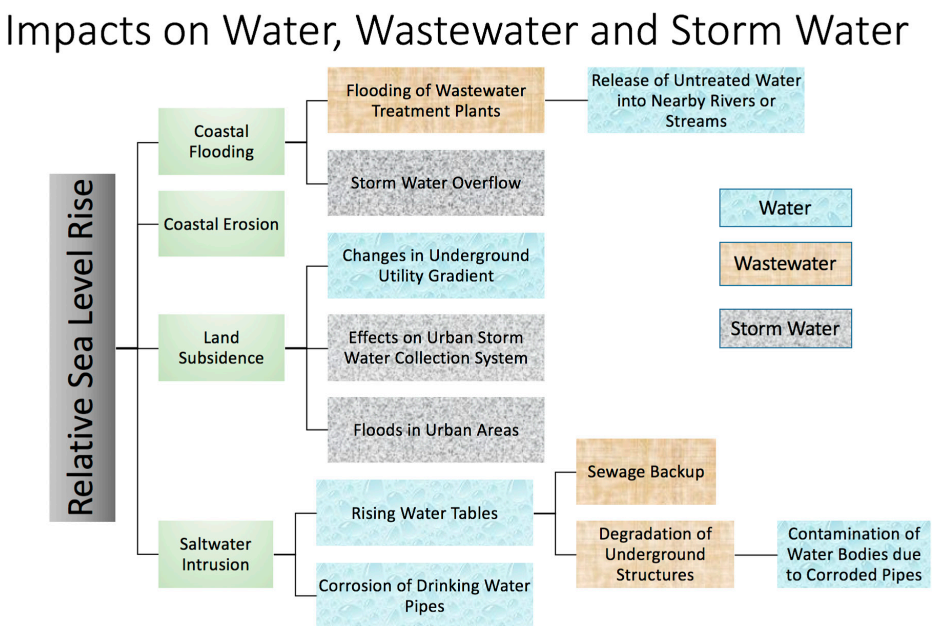

Figure 8. Specific impacts on water, wastewater and stormwater systems.

To deal with these impacts, different adaptation measures that can be adopted are discussed in the next section.

4.2. Adaptation Measures for Water Infrastructure

There are three approaches for adaptation of coastal areas in dealing with the sea level rise impacts on water infrastructure: (1) Protection; (2) Accommodation; and (3) Retreat. Protection is to manage the hazards by reducing their likelihood of occurrence. Accommodation is to manage hazards by reducing their impacts. Retreat is to manage hazards by reducing exposure in a planned manner [29–31]. For water infrastructure systems, various adaptation measures can be implemented related to each of these approaches as shown in Table 1.

(1) Protection: In the case of a flooding event, many components of water treatment facilities are at risk of failure due to inundation. Protection of water infrastructure facilities such as low-lying treatment facilities can be done using physical and green infrastructure. Physical infrastructure such as dikes and seawalls can be constructed or elevated to reduce the likelihood of flooding occurrence in treatment facilities. Similarly, green infrastructure such as beach dunes and coastal marshes are examples of ecological elements suitable for coastal protection [32]. Another effective green infrastructure solution is mangroves that can reduce coastal erosion and protect coastal areas from flooding. Mangroves reduce the height and energy of wind and waves passing through them, and thus, decrease their ability to erode sediments and to cause damage to structures such as dikes and seawalls [33]. In addition, mangroves reduce coastal erosion through binding soils together.

(2) Accommodation: To reduce the impacts of sea level rise on storm water drainage systems, pump stations can be used to more effectively collect storm water runoff and direct it to the receiving waters [34]. Enhancing storm water pumping capacity reduces the likelihood of sewage backup due to sea level rise and flooding. In addition, use of green infrastructure such as bioswales and rain gardens can reduce the impacts of sea level rise on stormwater drainage systems. Bioswales are storm water runoff conveyance systems that can absorb storm water runoff due to heavy rain. Bioswales filter the stormwater and store the water, and hence, reduce the pressure on sewage systems during heavy rainfalls and flooding. Rain gardens can be used as effective landscape elements to reduce storm water runoff. When implemented as landscape components of different city facilities and buildings, rain gardens can effectively reduce stormwater runoff and reduce the pressure on drainage systems under sea level rise.

Table 1. Adaptation measures in dealing with SLR impacts on water infrastructure.

SLR Impacts	Protection		Accommodation			Retreat		
	Dams, Dikes and Seawalls	**Dunes, Coastal Marshes and Mangroves**	**Increasing Pumping Capacity**	**Bioswales and Rain Gardens**	**Artificial Aquifer Recharge**	**Raising Elevation of Facilities**	**Controlled Groundwater Extraction**	**Storm Water Re-Use**
Damages due to land subsidence					X		X	
Degradation of underground utilities	X				X			
Saltwater intrusion into groundwater and estuaries					X		X	X
Sewage overflow		X	X	X		X		X
Inundation of low-lying treatment facilities	X	X	X			X		

Another important sea level rise impact on water infrastructure is saltwater intrusion into aquifers. Two measures can be taken to accommodate this impact. The first adaptation measure is artificial injection of storm water into aquifers. Through artificial recharge, storm water is collected and injected into groundwater aquifers through human effort. The artificial recharge can be done by surface water or outlet water from wastewater treatment [35]. The injected water increases groundwater tables and helps in overcoming sea water pressure. Artificial aquifer recharge has two benefits: (1) creating a barrier to saltwater intrusion; and (2) controlling land subsidence through maintaining groundwater levels. Another measure to accommodate salt water intrusion impact is building desalination plants. The drawback of desalination plants is their significant energy use.

(3) Retreat: There are different adaptation measures to reduce the exposure of water infrastructure to sea level rise hazard impacts. In order to reduce the exposure of low-lying treatment plants to sea level rise impacts and flooding, the elevation of these facilities should be raised. To this end, the codes need to be modified to determine the new requirements for the elevation of water treatment facilities. Raising the elevation of facilities reduces the exposure of facilities and pump stations to flooding. For example, the Deer Island water treatment facility in Virginia was elevated about 1.9 feet to accommodate potential sea level change for at least the first 50 or 60 years of the facility's service [36]. In some facilities, raising the elevation would not be effective. For new treatment facilities, the siting and elevations should be determined based on future sea level rise scenarios.

A retreat measure to deal with salt water intrusion into aquifers is controlling extraction rates. The rate of groundwater extraction and pumping can be adjusted to manage the groundwater levels in order to avoid land subsidence. One solution is to reduce the extraction rate for well fields near the shore combined with an increase in the discharge rate of wells in other areas [37]. This strategy enables managing groundwater levels in critical areas close to the coast. Another adaptation strategy is to substitute surface water for groundwater supply or collect and reuse storm water to control the extraction. Water reuse and conservation are essential components of adaptation in dealing with sea level rise impacts on water infrastructure. To this end, stormwater systems should be upgraded so that the collected water can be treated and reused for irrigation and other purposes. This approach creates a more decentralized way to capture and treat stormwater [38]. Hence, in addition to reducing water demand and need for groundwater withdrawal, storm water reuse reduces the pressure on groundwater sources by creating an additional buffer and balance in the systems [39].

5. Energy Infrastructure

5.1. SLR Impacts on Energy Infrastructure

The rising sea levels threaten energy infrastructure systems and pose a risk to the energy assets located in coastal regions. Changes in sea level and in the frequency and intensity of storm events will likely affect the way that energy is produced, delivered, and consumed [40]. Climate change is likely to increase the vulnerability of energy facilities in the coming decades. The number of U.S. energy facilities exposed to storm surge hazards could increase by 15% to 67% under a fast sea-level rise scenario [41]. As a case in point, Hurricane Sandy's impacts in New York City showed the significant vulnerability of energy facilities to storm surge events [42]. In the U.S., a great number of coastal energy facilities are located in areas exposed to 4 feet sea-level rise. An analysis made by [43] identified 287 energy facilities at risk of flooding, spreading throughout 22 coastal states. These facilities include natural gas infrastructures, electric power plants, and oil and gas refineries. There are four main impacts on energy infrastructure identified in the literature: (1) Coastal flooding; (2) Saltwater intrusion in energy utility assets; (3) Coastal erosion; and (4) Increased energy demand. Table 2 summarizes the sea-level rise impacts on energy infrastructure identified in the existing literature.

Table 2. Sea-level rise impacts on energy infrastructure.

Sea Level Rise Impact	Power Infrastructure	References
Coastal flooding	Damage to power plants Indirect: increased demand for power used in storm water drainage pumps	[34,38,44]
Saltwater intrusion in energy utility assets	Indirect stress: increased demand for power for desalination of water supply; Erosion into underground utilities lines and cables	[44]
Coastal erosion	Plant, grid, and substation damages. Exposure of energy assets to the environment	[45]
Increased energy demand	Increase in water pumps, desalination technology and energy intensive assets produce off-peak energy consumption to the electric grid	[44,46]

(1) Coastal flooding: Sea level rise in coastal communities will cause flooding of low lying energy infrastructures along the coast. There are two main sources of coastal flooding identified in the literature: coastal storm surges and the rise of sea levels [47]. Both coastal flooding impacts possess a high risk to energy infrastructure located in coastal areas. Coastal flooding affects three types of energy infrastructure assets: (1) power generation facilities; (2) electric transmission and controls; (3) electric substations. Power generation facilities are regularly located in coastal shores and near urban areas to have accessibility to cooling water for their generators and for the discharge of wastewater. For example, [44] identified that the coast of Florida is vulnerable to having the main sources of electric generation flooded by sea level rise. Also, along the U.S. Atlantic Coast, [34] identified 20 power plants located in New York City that posed potential treat, lying in a 10-ft elevation contour. In addition to the energy generation and distribution facilities, [11] identified that electric controller for water treatment plant and wastewater treatment plant in Miami-Dade County were also vulnerable to sea level rise and high storm surge events. Many interdependent infrastructure systems such as water, wastewater, and transportation systems depend on energy equipment and controller to sustain their services. If there is any power failure due to inundation of a substation, the substation ceases to work; subsequently, the linked sewage pumping stations are affected. This shutdown can cause floating of sewer pipes and damages to roads.

(2) Saltwater intrusion in energy utility assets: As mentioned in the previous section, saltwater intrusion is the contamination of groundwater with saltwater at high water table areas. Rising sea levels will increase the degradation of energy infrastructure materials with corrosion by saltwater intrusion due to inundation and groundwater contamination. In many urban cities and communities, energy transmissions are buried underground [46]. Zimmerman (2010) [38] pointed out that most of electric equipment in New York City located at ground level could get corroded easily given the fact that energy equipment is not designed to withstand saltwater exposure. In Florida, electric transmission lines are in direct contact with groundwater with the risk of being exposed to saltwater.

(3) Coastal erosion: Coastal erosion is a natural phenomenon that occurs when wave forces wear rocks, beaches and sands dunes. Many sea level rise scenarios do not take into account the effects that coastal erosion have on energy infrastructure systems. Coastal erosion can accelerate sea level rise effects significantly and it is extremely necessary to include coastal erosion in sea level rise scenario analysis to clearly identify the impacts of sea level rise and the adaptation measures that need to be taken. Sea-level rise and storm surges accelerate the coastal erosion and vice versa [45]. Studies conducted by [38,45,46] determined that many energy infrastructures are located in the proximity of coastlines, making them vulnerable to coastal erosion.

(4) Increased energy demand: With the rise of sea levels, and subsequent floods, there is an increased demand for power used in storm water drainage pumps to prevent overflow roads and also for desalination of water supply. Also, energy is needed to treat drinking water. The increase in energy demand affects energy infrastructure systems mainly because of the

interdependence between other infrastructure systems such as water networks and transportation networks. Water and wastewater pumping and treatment are major energy users. Transportation and communication networks are needed to maintain and operate the infrastructures [48]. Increased variability in water quantity and timing due to the projected changes in intensity and frequency of precipitation will have impacts on hydropower. The likely increase in the need for energy for pumping water implies more peak load demands, stresses on the energy distribution systems and more frequent blackouts. These will have negative impacts on local health and local economies [48]. According to [11], experiences with the recent extreme weather events have shown how the loss of energy supplies due to storms and floods can disrupt transportation and water treatment services, and also communication services which in turn complicates emergency responses related to health and safety. Figure 9 concerns the cascading impacts of sea level rise on different infrastructure systems. It shows that almost all impacts will ultimately increase energy demand in the future.

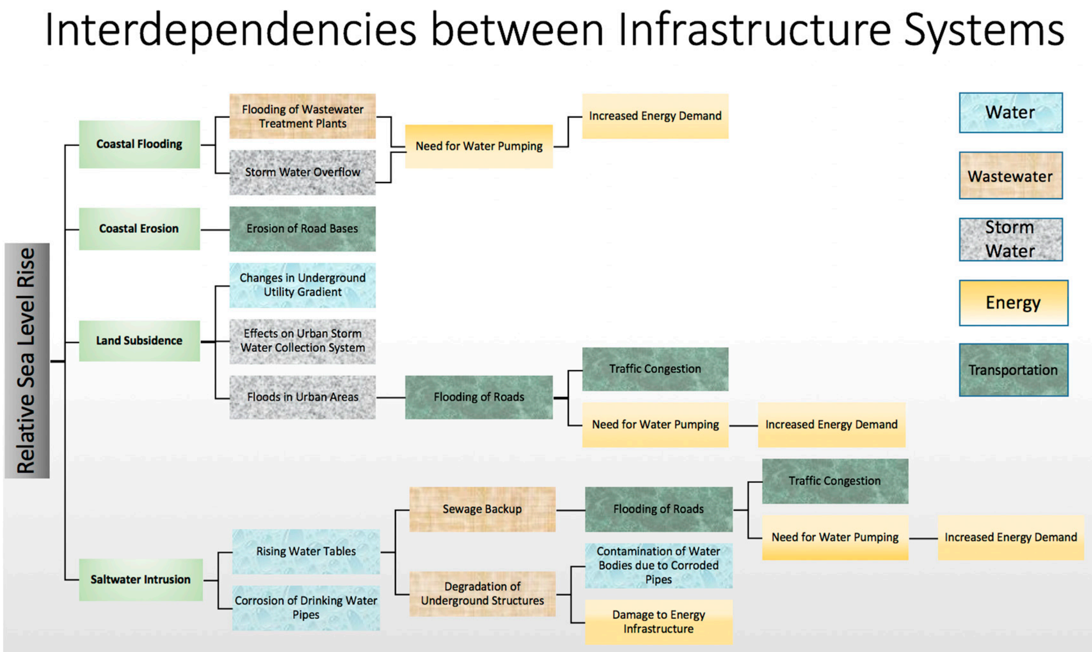

Figure 9. Cascading impacts of sea level rise on infrastructure systems.

5.2. *Adaptation Measures for Energy Infrastructure*

Most of the impact assessment and adaptation measure studies for energy infrastructure are conducted by the U.S Department of Energy in urban systems and vulnerable densely populated coastal areas [46]. Other studies such as the ones conducted by [38,44] were commissioned by the Senate of United States committee on energy and by Climate Change Energy Panel. Implementation of adaptation measures requires policies and management decisions that related to various sectors of the economy and levels of government. While most of energy infrastructure facilities are owned by the private sector, state and federal governments also have important roles in the regulation of energy infrastructure. The federal government can influence management decisions by providing information, regulatory supervision, research and technological development and market incentives. For energy infrastructure systems, various adaptation measures can be implemented as shown in Table 3.

Table 3. Adaptation measures in dealing with SLR impacts on energy infrastructure.

SLR Impacts	**Protection**		**Accommodation**	**Retreat**	
	Sea Walls	**Coastal Forest Rehabilitation and Beach Dune Restoration**	**Increase Power Generation and Transmission**	**Elevation of Energy Equipment**	**Use of Renewable Energy Sources**
Coastal flooding	X	X			X
Saltwater intrusion on energy utility assets	X			X	
Coastal erosion	X	X		X	
Increased energy demand			X		X

(1) Protection: Protection of energy facilities is achieved by "hardening" the structures, either by building new enhanced infrastructures or upgrading the existing infrastructures. Hardening energy infrastructure across the supply chain is part of the energy industry's responsibilities to ensure that the existing infrastructures will be able to deliver energy to its customers under extreme weather events. Some industries choose to make physical changes to its infrastructure to make it less likely to be damaged by extreme winds, flooding, or other weather events. According to Entergy Corporation representatives, they made a study that identified a number of potential hardening measures, such as replacing wooden transmission and distribution poles with steel or concrete and building levees around oil refineries. In response to more recent storms, such as Hurricane Isaac, Entergy representatives note that the implementation of these adaptive measures has paid off. They have experienced less infrastructure damage and have restored power to their customers more quickly than in previous storms [33].

Historically, much attention has focused on the use of seawalls to protect coastal areas and infrastructure facilities susceptible to rising sea levels. Recently, other methods of protection have proven to be more suitable, such as coastal zone management and ecosystem-based adaptation, including coastal forest rehabilitation or beach dune restoration [49]. The use of structural protection can be advantageous in areas that are highly developed. However, use of green infrastructure can be more appropriate in less developed and environmentally sensitive areas. In addition to being more cost-effective, green infrastructure solutions are environmentally friendly, and allow more flexibility to respond to future uncertain changes of sea levels. Despite the uncertainty in the rate of sea level rise that makes planning more difficult, it is known that not taking action is a deleterious response in dealing with uncertainty [50].

(2) Accommodation: As stated in the previous section, energy needs will increase because of new pumping for drainage, desalination, and cooling water [44]. The increase in electricity demand will require the construction of new power generation facilities not included in regional and cities' energy planning. Many power companies consider as part of their planning how to produce enough energy to support 120% of the forecasted demand. However, with sea level rise and its impacts, other infrastructures (e.g., pump stations) will increase their demand due to system deficiencies and the peak energy demand would exceed the plan, so energy blackouts will be more likely to occur. On the other hand, increasing power generation and transmission beyond the current planning scope is very difficult. The interdependencies between different infrastructure systems make it difficult to assess the amount of energy required for each infrastructure to adapt to sea level rise. It is necessary to implement a systemic adaptation measure considering the needs across various infrastructure systems. As mentioned by [38], urban cities are highly populated and, thus, it becomes difficult to build new power plants because land space is scarce.

(3) Retreat: A good method to reduce the exposure of energy infrastructure to flood damage is elevating critical infrastructures or using submersible, saltwater-resistant equipment. The elevation solution includes raising energy infrastructure equipment and assets that are vulnerable to the inundation of sea level and erosion by saltwater intrusion above the expected rate of sea level rise. Elevating vulnerable systems is the most effective adaptation measure to reduce the risk of failure of the electric system [46]. Although being the most effective method, elevation of energy equipment could not be the most cost-effective approach. Reference [38] showed that the expenses in elevating all the vulnerable assets in New York City would not be sustainable. The transmission lines and equipment serving the city are concentrated and provide relatively small flexibility for relocation. Another method to adapt energy infrastructure to sea level rise is to use renewable sources of energy. According to the National Renewable Energy Laboratory, the United States can meet 80% of its electricity needs in 2050 through renewable energy generation using current technology. In fact, renewable energy sources generally produce much lower emissions of greenhouse gasses (GHG), which is the primary anthropogenic driver

of climate change and consequently, sea level rise. Using renewable sources of energy generation will help reduce the amount of GHG in the atmosphere and, consequently, the effects of sea level rise. So, using renewable energy can be considered as a resilient method to adapt to SLR. Also, it is a way to reduce the dependence on electrical energy and give alternative options to provide energy to different infrastructure systems in a case of high energy demand.

6. Transportation Infrastructure

6.1. SLR Impacts on Transportation Infrastructure

The increasing global temperatures and sea levels, and changes in weather patterns have significant impacts on transportation infrastructure systems (e.g., roads, airports, railways, and ports). According to [51], sea-level rise is recognized as a major threat to transportation systems, especially in coastal areas, by increasing the number of flooding events, storm surges, and beach erosion. With a continued sea level rise, there will be a need for more frequent and extensive maintenance and rehabilitation of transportation infrastructure. With increased frequency and intensity of precipitation, transport networks will be inundated more frequently (due to nuisance flooding). Exposure to frequent cycles of inundation increases decay rate of transportation facilities and causes disruptions in these networks. In addition, these effects are combined with other impacts such as land subsidence, the extent of damages and disruptions will increase. Different studies have discussed various impacts of climate change and sea level rise on transportation infrastructure. Table 4 summarizes examples, from different literature sources reviewed, of the impacts of SLR on transportation infrastructure in different locations. It is found that there is a variation of the rising sea levels in different regions and also their impacts. This is due to the difference in the vulnerability of each region to increased sea level. In some regions, the increase in sea level should be large so that the impacts on transport systems would be significant. However, in other regions, small increases in sea level can have extreme impacts. In this section, in particular, the impacts of sea level rise on coastal road networks as well as relevant adaptation measures are discussed. While the focus is on road infrastructure, the impacts and adaptation measures for other transportation facilities (e.g., ports, airports, and transit systems) are briefly discussed.

Table 4. Potential damages to transportation infrastructures around the globe retrieved from different literature sources.

Location	SLR	Potential Damages to Transportation Infrastructures	Source
Coastline along MexicanGulf	1.2 m	27% of major roads 9% of rail line 72% of the ports	[52]
Washington DC US	0.59 m 0.1 m	15 km roads, 3 km railroads 10.5 km streets	[2] [53]
Egypt	0.5 m	11.73% whole network or 23 km roads	[54]
California US	1.4 m	1600 mile roads, 180 mile Highway	[14]

6.2. SLR Impacts on Roads

Among different types of transportation infrastructure, roads are the predominant mode in the daily lives of community members. In addition, road networks are significantly vulnerable to sea-level rise impacts over time. The impacts of sea-level rise on road infrastructure are mainly: (1) Erosion and subsidence of road bases; (2) Flooding of underground tunnels and low-lying infrastructures; (3) Inundation of roads and rail lines; (4) Traffic congestion; and (5) Infrastructure damage due to increased storm intensity.

(1) Erosion and subsidence of road bases: One of the biggest problems that road networks are dealing with is the erosion of structural layers. Erosion is a natural phenomenon that threatens roads that are the proximity of seas. For example, on the West Coast of the United States, problems with flooding are not a major concern, while erosion is expected to cause significant damages. For example, about 120 miles of highways and 730 miles of roads along the coast of California are at risk of erosion. In addition to the aggravating effects of rising sea levels, human interventions amplify coastal erosion by avoiding the coastal displacement through breakwaters, blocking sand in upstream reservoirs and sand mining [55].

(2) Flooding of roads and low lying infrastructure: According to [56], more frequent extreme precipitation events may have significant consequences for transportation, resulting in more frequent flooding and pushing the capacity of existing drainage systems of roads. For example, according to [57], various road networks along the Pacific Coast in California are vulnerable to flooding events exacerbated by sea level rise. The vulnerability analysis of road networks in California showed that under the present condition almost 2000 miles of roads are at risk of flooding. This number will increase by 175% with an increase of 1.4 m of sea level rise. Most vulnerable roads are located in the San Francisco Bay region [57]. In another example, the increased risk of severe flooding in Florida's low-lying terrain can cause inundation of roads and structural damage due to increased water table levels [58].

(3) Traffic congestion: The effects of sea level rise may indirectly spread through the transportation system and subsequently affect the system performance. In addition, extreme rainfall events and more frequent flooding may disturb traffic management systems. These impacts can disrupt traffic flow and cause significant congestions. The flooding of a major road can cause changes in traffic flow, and subsequently cause congestion in other roadways that may not be able to support the traffic demand. This impact would lead to an operational failure of the system and also increase travel times and extend delays because of rerouting. In addition, the inundation of a critical access road could cause transportation connectivity problems by blocking access to some areas [58]. According to Miami Herald newsletter, the city of Miami Beach has put into action an aggressive and expensive plan to combat the impacts of sea level rise. As some streets continue to flood because of the high tide events, a lot of important roads of the city become completely flooded during storm events causing damage to cars, homes, and business. With that, the traffic becomes chaotic causing delay in travel time and a lot of accidents. The city continues rolling out its plan and will spend more than $400 million over the next five years on adaptation methods to mitigate the impacts of SLR.

(4) Inundation of roads and rail lines: As said by [55], to consider the impacts of inundation, roads that pass through land areas with an existing elevation above sea level of less than or equal to 23 feet are considered to be vulnerable to storm surge inundation by 2100, and roads that are located in or pass through land areas with an existing elevation above sea level of less than or equal to 18 feet are considered to be vulnerable by 2050. In a report of Hampton Roads Planning District Commission, [59] highlights damages to road transportation in Atlantic coast, in a case study of Virginia State. The assessment which was analyzed by GIS software shows that around five hundred miles of roadways are at risk of permanent inundation due to increasing sea levels. A simulated storm surge model, developed by [56], for the central Gulf Coast, demonstrated that with storm surge at 23 feet, more than half of the area's major highways (64% of interstates and 57% of arterials), almost half of the railroads, 29 airports, and practically all of the ports are prone to inundation. Besides that, according to [55], even temporary inundation from nuisance flooding and storm surges can disrupt the road networks. During the period of inundation, roads may not be passable, and would not serve as an emergency evacuation or recovery route.

(5) Infrastructure damage due to increased storm intensity: During flood events, one of the major impacts on transportation infrastructure is the damage to storm water pipes. According to [60], storm water pipes are designed to balance the hydraulic forces that act inside as well as the

earth forces on the top of it. The pipes are installed at a critical depth under the ground which should be stable and inexpensive. When a flood occurs, this balance is disturbed because of the additional weight of water. Due to this differential forces acting on the pipes, they start to float to the surface causing damage to the roads. This phenomenon may also cause damage to the roads that are unaffected by floodwater. In some cases, it might be possible to pump the water out of the flooded areas before damage happens. In addition, prolonged flooding can damage pavement substructures. Most base courses are installed above the water table [58]. The roadway surface will remain stable if the base stays dry, but as soon as the base is saturated, the roadway can quickly deteriorate. In addition, due to the reduction of soil storage capacity, roadways that are frequently flooded are more likely to experience pavement damage.

6.3. Adaptation Measures for Transportation Infrastructure

Similar to water and energy infrastructure, three approaches to deal with sea level rise impacts on road infrastructure were identified: (1) Protection; (2) Accommodation; and (3) Retreat. Each approach has its merits and disadvantages. City planners and decision-makers need to choose an appropriate adaptation based on an evaluation of different factors such as population, city size, and significant features like heritage sites or political issues [4,53,61]. For road infrastructure, various adaptation measures can be implemented related to each of these approaches, as shown in Table 5.

(1) Protection: To select an appropriate protection measure, it is important to consider the geological characteristics of an area. For example, using dikes along the North Sea is recognized as an appropriate method in protecting low lying roads. However, in Florida, dikes are not suitable due to its porous ground condition [62]. Topological features of each region also provide an opportunity to better protect vulnerable regions against sea level rise impacts. In some cases, second dike lines or road dams can be used to protect lands from flood when the first dike line is damaged [63]. In case of undeveloped low lying areas, roads can play the protective role of dikes against the sea. So, it is reasonable to use roads that are parallel to the coast to make a real dike system. In addition, transportation agencies sometimes build culvert bridges along the dikes to let water pass through the road [64]. Another protection measure is the construction of seawalls to protect road infrastructure adjacent to the coast. Seawalls have been proved to be effective in reducing the effect of erosion. They have been built for many years in coastal urban cities. Although this protection measure has been effective, sometimes it is not sufficient to withstand the impacts of sea level rise. Seawalls have the same vulnerability as other hard infrastructures when it comes to structural stability. In previous studies, findings identified that around 92% of communities that have engaged in the construction of seawalls felt that this protection measure was not sufficient to deal with sea level rise impacts [65]. Another important way to protect vulnerable areas is the nourishment of coastal shores through beach replenishment. This method consists of replacing sand from beaches and coastlines that have been eroded by the effects of sea level rise and waves with new sand in order to improve the stability of infrastructure and buildings. If this action is taken, the sandy areas will naturally adapt to the changing condition of sea level and it would be a flexible choice with a low cost and a good adaptation for the future of seaside cities. Beach nourishment has been utilized as an effective measure in different coastal regions as a relatively inexpensive measure compared to other adaptation measures like dikes. However, beach nourishment does not solve all sea level rise problems in the long term. Many coastal urban areas that have implemented beach nourishment had to constantly monitor shorelines and continuously keep refilling beaches and coastlines.

(2) Accommodation: Elevating roads and existing structures is an example of accommodation of infrastructure to reduce the impacts of sea level rise. Elevating the existing roads has certain advantages and disadvantages. When a road is raised, the vulnerability for flooding remains unchanged, however, it is probable that the impacts of flooding will cause less damage if this method is implemented. It will be more economical to prevent the damage than to repair it [66].

Another accommodation measure is to use pervious materials for paving roads in low traffic residential streets. Nevertheless, for high-speed and high traffic volume roads, the drainage capacity of the roads should be enhanced from the roadbed. On the other hand, this method will probably cause some difficulties for surrounding areas. The water stands in the properties along the roads and could be a good place for mosquitoes to live, so it will be against sanitation and urbanization policies. Also, it is a town's responsibility to inform inhabitants about the future need for elevating their houses [55,58]. Another accommodation measure is to use pumps to drain storm water away from streets. Due to sea level rise, the frequency of floods and storm surges increases, and thus the existing systems will not be enough to drain storm water [38]. The elevation of streets and nearby properties are important factors affecting the direction of drainage flow. In a case study in Bangladesh, [67] presented the benefits of using drainage systems to pump the storm water away from the streets. In another example, in Ocean City of Maryland, there is an urban design role in order to drain the water on streets that are most prone to flooding during storm events. In the United States, thousands of dollars are spent on street drainage check valves to avoid backing up into streets and this method is considered as reasonable and affordable, because if the checking does not occur periodically, the impacts will force owners to elevate their land because of sea level rise and this will be much costlier [64].

(3) Retreat: An example of retreat measure is to take anticipatory action to limit the development of vulnerable areas exposed to sea level rise risks. If new roads are constructed beyond the restricted stripes, the probability of threat to properties and people will increase. Reference [68] stated that, in addition to the hard and soft adaptation measures against sea level rise for transportation infrastructure in coastal cities, there is another kind of practical adaptation measure for the northeastern part of the US and it is land-use policies. With zoning actions, it would be possible to restrict areas that are at risk with different strategies, such as setback line construction, removal of dangerous buildings, and purchase or request of unoccupied areas near the sea to allow wetlands and beaches to be extended. Providing the legal foundation for governments to buy-out vulnerable districts after the rise of sea levels is a great solution to reducing the threat to these areas. This method has been used since 1986 in France, to manage the expansion of urban zones and mitigate future risks [69]. It should also be mentioned that any attempt to reduce the amount of greenhouse gas emissions (GHG) will lead to a decrease in the rate of sea level rising, increased temperatures and precipitation, thus allowing for 30% less impact on infrastructure systems [69].

Table 5. Adaptation measures in dealing with SLR impacts on transportation infrastructure.

SLR Impacts	Protection		Accommodation			Retreat	
	Dikes, Road Dams and Seawalls	**Beach Nourishment**	**Elevation of Roads and Existing Structures**	**Use of Pervious Materials on Roads**	**Improving Drainage Capacity**	**Limit the Development of Vulnerable Areas**	**Reduce Greenhouse Gas Emission**
Erosion and subsidence of road bases	X	X		X	X		X
Flooding of roads and low lying infrastructures	X			X	X	X	X
Traffic saturation			X		X	X	
Inundation of roads and rail lines			X	X	X		
Infrastructure damage due to increased storm intensity			X		X		

7. Implementation and Decision-Making Challenges

The extent and nature of sea level rise impacts on infrastructures vary based on the specific characteristics (e.g., soil condition, ecological conditions, and land topography) of each coastal region. In addition, the extent of impacts varies depending on geophysical risk exposure, adaptive capacity and resilience, and level of economic development of the community [70]. Thereby, adaptation measures for different infrastructure sectors usually require a complex, site-based analysis of different conditions and impact patterns [49]. The implementation of sea level rise adaptation measures for infrastructure systems involves various challenges. Some of these implementation challenges are discussed below.

(1) Capital Investments: First, implementation of adaptation measures requires significant capital investments on top of expenditures needed for maintenance and rehabilitation of infrastructure. While the current infrastructure funding sources are not sufficient for addressing the normal condition investment needs, additional expenditures for adaptation will be significantly challenging. In addition, although investments in adaptation measures will include long-term economic payoffs, the uncertain and long-term nature of benefits makes economic evaluations of adaptation investments difficult. However, adapting infrastructure to sea level rise impacts presents significant opportunities as long as actions are taken early. In addition, adaptation actions should be selected based on the evaluation of various criteria and consideration of future uncertainty. Each adaptation measure has its own merits and costs. City planners and decision-makers need to choose appropriate methods based on the evaluation of different factors such as population, city size, and other considerations such as heritage sites or political issues [4,53,61].

(2) Information Gathering: Prior to the development and implementation of sea level rise adaptation measures, it is necessary to gather all the required information related to possible sea level rise scenarios and projections, various impacts, and feasible adaptation measures. This process includes risk and vulnerability assessment of infrastructure systems. The information obtained from risk and vulnerability analysis enables decision-makers to identify exposed infrastructure, the extent of vulnerability, and subsequent risk consequences in order to efficiently allocate their limited resources. Mapping exposure of infrastructure can lead to the identification of facilities that are vulnerable to sea level rise under different projections of sea level rise. This information provides a baseline for prioritization of infrastructure facilities based on their vulnerability. For instance, [53] assessed the damages of basic infrastructures such as public buildings, streets, railroads, metro systems, public safety institutions (fire stations, police stations, hospitals), educational institutions and governmental institutions, in Washington, D.C., under different sea level rise scenarios using GIS software. This sort of analysis provided a practical assessment of important infrastructures vulnerable to flooding. A robust assessment of sea level rise impacts and infrastructure vulnerability would require: (i) reliable projections of future sea level rise; (ii) improved flood and storm surge scenarios based on future climate change patterns; (iii) consideration of future population and land use changes; and (iv) quantified assessment of uncertainty.

(3) Public Education and Community Engagement: Public education and community engagement are essential to help communities to understand: (i) how they can be directly affected by sea level rise now and in the future; and (ii) what adaptation actions should be taken by local community decision-makers. The inclusion of community values at the early stage of adaptation is essential. Identifying community values and priorities provides a strategic direction for decision-makers to choose adaptation methods that are compatible with specific needs of individual communities. This citizen engagement approach offers an opportunity not only to improve public understanding but also to gain public support. In addition, public education and community engagement should take place throughout the adaptation process to ensure transparency in the decision-making process by making information available from a wide

variety of sources and holding public information seminars, workshops and conferences [71]. Public education and community engagement are required by law in some regions as part of local planning processes [72]. Sea level rise has started gaining public attention. However, the impacts and the need for adaptation actions are still not completely understood by the public.

(4) Uncertainty in Sea Level Rise Projections: According to the Intergovernmental Panel on Climate Change's [73] assessment report, the average rate of global sea level rise was 0.17 cm/year during the 20th century, 0.18 cm/year from 1961 to 1993, and 0.31 cm/year from 1993 to 2003. Global climate models suggest that global average sea level might rise 18–59 cm by 2100, if ice sheets continue to melt at the rate observed from 1993 to 2003. If the rate increases at the same trend as global temperatures warm, total sea level rise by 2100 might be 10–20 cm greater than the average projections. The upper bound for sea level rise projection is difficult to estimate [73] because of the uncertainty related to the rates at which the ice sheets will melt [74]. Hence, the implementation of adaptation measures should consider uncertainty. Uncertainty related to future rates of sea level rise and its impacts on water, energy, and transportation infrastructures involves two important considerations: the timing and the magnitude of sea level rise. Sea level rise timing determines if current decisions on capital investments need to incorporate the sea level rise impacts at the end of the useful life of infrastructure systems. If a slower sea level rise is projected and impacts are expected after the end of the life cycle of infrastructure, the systems will not require any adaptation measure. On the contrary, if changes in sea level are projected to occur rapidly, planning decisions need to account for implementing adaptation measures earlier than the end of life of infrastructure facilities [75]. The magnitude of sea level rise impacts determines to what degree an adaptive action is warranted. Underestimation of sea level rise impacts can lead to ineffective adaptation capital investments. Both types of uncertainty related to timing and magnitude of impacts make investment decisions complicated [76]. Hence, robust adaptation requires sophisticated decision-making processes, given how little we know about future sea level rise effects at the regional level. Starting this process is important, specifically at the early planning stages [49]. Decision-makers can mitigate impacts and make adaptation easier by proactively planning for different scenarios of sea level rise impacts.

(5) Costs of Adaptation: The need for water, energy and transportation infrastructure investment over the coming decades is already significant. Rising sea levels may also affect where infrastructure is built and how it is operated. There will also be a need for investment in additional infrastructure, dedicated specifically to protection against rising sea levels, such as flood protection, drainage, construction of seawalls, and other adaptation methods stated at the previous sections, as well as retrofitting to improve the resilience of the existing infrastructure. Infrastructure adaptation usually exceeds the cost estimates making the decision-making processes more complex. The cost of protecting coastal assets and infrastructure can be significant. For example, shoreline retreat in the United States is projected to cost between $270 billion to $475 billion for each meter of sea level rise [1].

(6) Maladaptation: To mitigate the potential impacts of rising sea levels on infrastructure systems, it is necessary to plan and to implement cost-effective adaptation strategies. To avoid maladaptation, it is extremely important to evaluate the effectiveness of the adaptation methods used. Maladaptation is considered as the poor selection of adaptation measures such that the changes in the infrastructure systems become less effective as time goes by until the infrastructure systems become dysfunctional. It is a significant challenge to anticipate the impacts of sea level rise and to take timely action. Maladaptation may occur if decision-makers fail to implement appropriate adaptation measures at the right time. The key element to overcoming this challenge is to analyze the performance of physical networks and the long-term impacts under various sea-level rise scenarios. However, this analysis can be affected by the condition of physical networks, the vulnerability of network links to sea level rise impacts, and the decision-making behaviors of the institutional agencies managing physical networks [77].

8. Concluding Remarks

This study presented various impacts of sea level rise on infrastructure systems in coastal areas and discussed adaptation measures to mitigate the adverse impacts of sea level rise based on a systemic review of the existing literature. The contributions of this study are threefold: (1) identifying general and specific impacts of sea level rise on infrastructure systems; (2) understanding the dependencies among various impacts and adaptation measures across different infrastructure sectors; and (3) highlighting the challenges of the implementation of adaptation measures in response to sea level rise impacts.

The major impacts of sea level rise on infrastructure systems in coastal areas are coastal flooding, coastal erosion, land subsidence, and saltwater intrusion. These impacts will affect various infrastructure systems. Different adaptation measures were identified to protect, accommodate and retreat the infrastructure systems in response to sea level rise risks. While the identified impacts and adaptation measures from the reviewed studies in different regions are similar to some extent, the differences between geographic locations, soil conditions, the topography of the area, and policies and regulations affect the type and extent of impacts, as well as the suitability of adaptation measures. This study did not consider how specific traits of coastal areas would affect the sea level rise impacts and the suitability of adaptation measures. Nevertheless, the findings of this study will inform decision-makers about a wide range of sea level rise impacts and the benefits of different adaptation measures in order to enhance the resilience of infrastructure systems in coastal areas under sea level rise impacts. Future studies can build upon the findings of this study to further examine the sustainability and effectiveness of the identified adaptation measures and the co-benefits and tradeoffs in implementation of these adaptation measures across different infrastructure systems. In addition, future studies can further evaluate innovative adaptation measures such as green infrastructure, coastal renewable energy, and emerging coastal management practices. Assessment of innovative financing approaches [78,79] to implement infrastructure adaptation decisions is another dimension that future studies need to address.

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