Sea-Level Rise Adaptation: A Review of Decision-Making Approaches and the Role of Operations Management

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Abstract

Problem definition: Sea-level rise (SLR) presents substantial risks to ecosystems and densely populated coastal regions, necessitating integrated solutions and informed decision-making. However, prevailing adaptation tools and frameworks, often reliant on economic and policy methodologies, exhibit notable sensitivity to uncertainties and are vulnerable to biases from diverse stakeholder inputs, thus constraining coordination and integration. To confront these challenges, Operations Management (OM) techniques provide a systematic approach that accommodates uncertainties and multiple objectives. ***Methodology/results:*** This paper presents a comprehensive review of decision-making models for sea-level rise adaptation, with a specific emphasis on critical infrastructure systems. We categorize pertinent literature according to predefined criteria including the type of system addressed, adaptation strategy, stakeholder involvement, modeling approach, and solution methodology. In a broader sense, this paper explores the extent to which the reviewed adaptation strategies have been incorporated into structured adaptation decision-making models and identifies research gaps in this field. Additionally, it seeks to introduce the problem to the OM community, presenting ways in which OM research can contribute to convergence research on this critical topic. ***Managerial implications:*** Our review highlights a growing interest in utilizing decision-making frameworks to enhance infrastructure resilience. However, significant gaps exist, presenting substantial opportunities for the OM community to contribute to and bridge these research gaps through interdisciplinary collaborations. By identifying research gaps and offering insights into structured adaptation decision-making models, this paper aspires to encourage active participation from OM researchers in tackling the complexities and challenges of SLR adaptation.

Keywords: sea level rise, adaptation, critical infrastructures, decision-making, resilience

1 Introduction

Eustatic sea levels are rising due to the thermal expansion of the ocean and the melting of glaciers, which, combined with land subsidence, tectonic activity, and sedimentation are projected to accelerate relative sea level rise in the future [6]. As a result, a large proportion of the World's coastlines, its population, and ecosystems will be exposed to the increasing risk of coastal flooding. The risks and challenges presented by sea-level rise (SLR) are not limited to inundation. Higher water levels also modify shoreline hydrodynamics, drive long-term coastal erosion, and increase saltwater intrusion into coastal freshwater aquifers. Given the myriad of challenges presented by SLR, we must adapt to these changing conditions by developing broad, cross-cutting, and integrated solutions that prioritize adaptation decision-making. In response to these challenges, several adaptation tools and frameworks have been developed by governmental and non-governmental organizations including the Adaptation Support Tool (AST) developed by the European Commission and the European Environment Agency (EEA) [43], AUDACIOUS (Adaptable Urban Drainage) [22], USAID Toolkit [217], the Community-based Risk Screening Tool for adaptation and livelihoods (CRiSTAL) developed by the International Institute for Sustainable Development (IISD) and its partners [96], PEOPLES framework developed by the United Nations Development Programme (UNDP), ADAPT tool developed by the World Bank [77] among many others [31, 162]. Despite these efforts, the majority of these strategies are based on economic evaluation methods such as Cost-Benefit Analysis (CBA), priority ranking, and weighted index-based preference selection methods, designed to guide adaptation decision-making. These methods can be subjective as they are influenced by personal biases and preferences of the decision-makers, leading to a lack of transparency and difficulty in explaining the results. Additionally, they are highly sensitive to uncertainties.

To effectively address the intricate and evolving challenges posed by climate change adaptation, Operations Management (OM) paradigms are poised to offer quantitative frameworks to analyze complex systems and support informed decisions grounded in data and incentives. In the realm of sustainability and enhancing infrastructure resilience, particularly against sea-level rise, leveraging OM has the potential to expand our knowledge frontiers through two avenues. First, while sudden onset disasters have been extensively studied in Humanitarian Operations Management [41], the exploration of responses to slow-onset disasters like sea-level rise remains relatively uncharted within the OM community. Addressing these slow-onset disasters requires strategic decisions on infrastructure adaptation, such as comprehensive redesign or reinforcement strategies, distinct from the traditional problems addressed in humanitarian OM, which are primarily associated with immediate response scenarios. Additionally, navigating infrastructure adaptation decisions involves modeling the interconnectedness between systems with diverse structures, changing dynamics, and varying stakeholders. Furthermore, while infrastructure adaptation and engineering interventions are crucial, they must be implemented with sensitivity to the social and economic disparities that often exacerbate vulnerabilities to climate impacts. Equity in adaptation decision-making involves ensuring that marginalized communities, who are disproportionately affected by climate change, have a voice in the planning and implementation processes. From these perspectives, OM can bridge natural sciences, engineering, and social studies by tying them together with effective, equitable, and actionable decision making through empirical and qualitative research. Understanding the dynamics of the slow-onset disasters, their complexities, and interconnectedness of infrastructure can inspire OM-led research to produce innovative ***modeling*** approaches for decision-making processes in such contexts.

Second, devising optimal plans and operational frameworks demands the design of novel and actionable ***solution*** methodologies. Enabling resilient and smart infrastructure involves the utilization of extensive datasets many of which are network-based, high resolution spatio-temporal and unstructured data. Confronting these challenges inevitably propels the advancement of methodologies reliant on data-driven modeling and decision-making. In this regard, OM methods, with their emphasis on designing efficient systems and processes with focus on resource allocation in dynamic and uncertain environments, can distinguish themselves from traditional approaches in adaptation decision-making centered around simplified scenario-based planning or econometric approaches [144, 176], thus offering great opportunities to develop new research tracks to the OM society, as well as providing practical decision-making support to practitioners and stakeholders.

The potential and the need for more OM research addressing the compelling societal challenges and sustainable infrastructure have been recently recognized by the OM community several researchers and calls were made in this direction [24, 49, 112, 126, 236]. Increasing number of papers have emerged in the OM literature tackling sustainability and adaptation problems related to climate change in the context of supply chain management [82, 110, 158], disaster preparedness [193], farming [5, 64, 90], water [25, 58, 247], energy [166, 168], real estate [207], transportation [233], and other critical infrastructure [111, 144, 176, 232].

A few papers in the OM literature focus on the challenges posed by SLR. Earlier works have studied the cost-effective design of dikes [48], economic standards for coastal protection [72], and levee installation planning [164]. In more recent studies, Jenkins et al. [109] propose a cost-benefit evaluation approach for designing dikes and levees to mitigate SLR-induced flooding. They employ a multistage stochastic program with recourse to minimize overall expected costs, considering both flood and investment costs under various SLR scenarios. The model, tested using Boston as a case study, demonstrated significant cost reductions, offering a practical tool for decision-makers to effectively assess and mitigate flood risks in urban coastal areas. Bagharsad et al. [27] propose models to prioritize stormwater infrastructure improvements, addressing the dual challenges of aging infrastructures and climate change. These models consider both horizontal and vertical equity alongside efficiency, with a case study in Miami showing their effectiveness in promoting equity and efficiency under SLR projections. Amer et al. [10] tackle the vulnerabilities of on-site wastewater management systems to SLR using a mixed-integer linear programming model. Using a case study in Miami-Dade County, their study evaluates hybrid configurations of centralized and decentralized systems, focusing on the trade-offs between cost and resilience. A common and crucial aspect in these recent studies is they are the products of OM led multidisciplinary work exemplifying the call for active and leading participation of OM researchers in addressing societal challenges through convergent research.

By applying Operations Management (OM) techniques, decision-makers can suitably manage the risks and uncertainties associated with SLR, enabling them to make informed choices regarding adaptation strategies. Key steps in utilizing these techniques include identifying the problem, decision variables, objectives, and constraints in societal or community contexts. However, employing OM techniques for SLR adaptation presents unique challenges, including: (1) deep uncertainty in SLR projections and their impact on coastal systems; (2) high multidimensionality requiring integration and collaboration with multidisciplinary teams; and (3) a large number of stakeholders with varying priorities necessitating coordinated decision-making. Overcoming these challenges is essential for establishing priorities, defining unified objectives, incorporating comprehensive constraints, and developing holistic and robust solutions for SLR adaptation.

Deciding on the optimal portfolio of adaptation strategies depends on various factors such as the specific geographic location, the infrastructure system being considered, the severity of the SLR impacts, and the availability of resources. In addition, the effectiveness of certain adaptation strategies may depend on other strategies that are implemented simultaneously, making it difficult to evaluate their individual contributions to the overall system resilience. This means that models must not only consider the effectiveness of each strategy independently, but also the synergies and interactions between strategies when assessing the overall system performance. For instance, building sea walls may provide short-term protection from flooding, but it may also have negative ecological impacts and reduce public access to the shoreline. Overall, determining the optimal set of adaptation strategies that provide the greatest overall benefit and minimize negative impacts is a complex and challenging task that requires careful consideration of multiple factors and stakeholders and a clear understanding of the potential adaptation alternatives, their consequences, and limitations.

With an understanding of the aforementioned challenges, this paper provides a comprehensive review of SLR adaptation strategies for various critical infrastructure systems and examines how these strategies can be integrated into decision-making models, discussing their potentials and limitations. In a broader sense, it explores for the general reader the extent to which the reviewed adaptation strategies have been incorporated into structured adaptation decision-making models and identifies research gaps in this field. Additionally, it seeks to introduce the problem to the OM community, presenting ways in which OM research can contribute to convergence research on this critical topic. By identifying research gaps and offering insights into structured adaptation decision-making models, this paper aspires to encourage active participation from OM researchers in tackling the complexities of SLR adaptation.

The structure of this paper is as follows: Section 2 provides an overview of strategies proposed and employed for infrastructure adaptation to SLR grouped under three categories: protection, accommodation, and retreat. Section 3 provides a discussion on various adaptation decision-making paradigms, including models based on prediction-first, robust, and adaptive approaches. Emphasis is placed on objectives, decision variables, and related aspects. section 4 presents a detailed analytical review of infrastructure-based adaptation strategies. In this section, various adaptation schemes, their use cases, and integration in adaptation decision making models are discussed. Finally, Section 5 addresses the identified research gaps and how OM approaches can play critical role in convergent research in enhancing infrastructure and community resilience to climate-change based stressors.

2 Adaptation Strategies for Sea-Level Rise

Adaptation strategies can be broadly categorized into three main approaches: protection, accommodation, and retreat. Protection involves reducing or eliminating potential hazards by constructing structures like dams, dikes, levees, and dunes. Accommodation focuses on minimizing damage by making structural changes to existing systems or adjusting their operation. On the other hand, retreat involves reducing exposure to risks by relocating coastal communities or critical coastal system components. Next, we elaborate on these strategies with several examples from practice.

Protection - Protection strategies involve both hard (or gray) and soft (or green, eco-system-based) defensive measures to mitigate the impacts of rising seas. Dikes, dams, seawalls, and levees are examples of hard or gray protection measures, while beach nourishment, mangroves, oyster reef restoration, and living shorelines are all examples of nature-based or green protection measures.

Conventional shoreline defense strategies as illustrated in Figure 1, primarily comprise engineering measures that are commonly employed to protect coastlines from future risks associated with SLR. For instance, China has implemented an extensive network of over 8,000 miles of seawalls [135]. Seawalls are compact and cost-effective defensive structures, mitigating damage caused by floodwaters and storm winds. A wide range of seawall designs exists, from steel seawalls to eco-friendly riprap solutions. Each design has its unique advantages and disadvantages. However, designing a seawall system necessitates careful consideration of various factors, including the characteristics of the water body, such as depth, salinity, and currents.

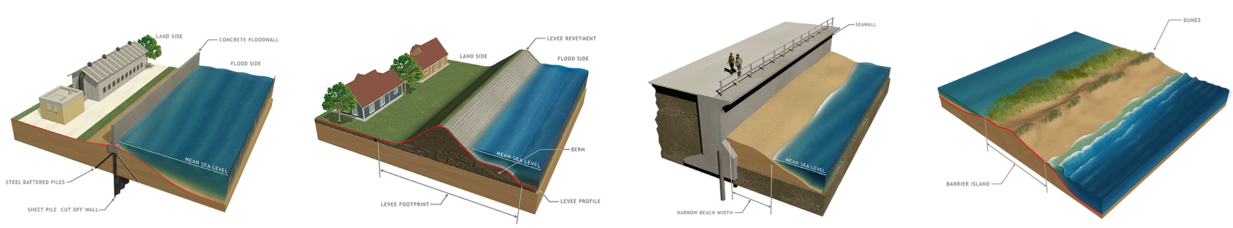

Figure 1: Different forms of protection measures. From left to right: Flood wall, Levee, Seawall, Dune. Source: Army Corps of Engineers [1]

Additional hard defense structures include dikes (levees), dunes, dams, and storm surge barriers. Levees can be strategically placed to provide partial shoreline protection in specific locations. Thus, when designing a levee system for optimal flood protection, it's essential to recognize that different combinations of levees may lead to varying inundation patterns, potentially increasing flooding in unprotected areas [164]. Critical decisions in this context involve determining the ideal locations, layouts, and heights for each levee segment along the shoreline, as outlined in [94].

Dikes, or dike rings, normally run parallel to a body of water such as a river or a sea. They are onshore structures constructed to protect low-lying areas against flooding and are widely used in countries with low-lying geographies such as Vietnam, Bangladesh, Thailand, the Netherlands, and parts of the United States. The Netherlands has the most famous dike system (known as the Dutch

Dike) extending for over 13,500 miles, with over 53 dike ring areas with safety standards exceeding 1/1000 per year [51]. Dike systems could be homogeneous or non-homogeneous. A homogeneous dike means that all parts in the dike ring have the same characteristics. Whereas a non-homogeneous dike system consists of different segments with different characteristics [48]. When designing a dike system, the optimal dike height that achieves the balance between minimizing investment costs and maximizing flood protection is the most important decision to make. In the non-homogeneous case, decision-making is more complex as it has to be made simultaneously for each segment.

Optimizing the dike design has widely been studied in the literature, such as in [48, 51, 205, 220]. Despite their functioning as flood defense structures, hard measures can generate adverse effects such as accelerated erosion, downdrift scouring, disturbance of sediment supply and beach reduction, restricted public access, ecological damage, etc. [181]. Therefore, soft protection measures, in some cases, could offer a more feasible solution for coastline protection or could be adopted in integration with a hard defense structure. Such measures usually involve nature-based solutions, such as rain gardens, bioswales, and rainwater harvesting, reduce and treat stormwater at its source [53, 219]. These solutions have proven beneficial by preventing flooding and alleviating the burden on traditional drainage systems. Additionally, they offer multiple ecological benefits and contribute to improving water quality. Acting as natural filters, they effectively remove pollutants, resulting in enhanced water quality before it reaches rivers, lakes, and other water bodies.

In addition to the hard and soft protection measures, synergistic applications of wave farms are also proposed for coastal management. Wave farms are arrays of wave energy converters that are considered for protecting the coasts, in addition to their main function of generating renewable sources of energy. They help mitigate coastal erosion and flooding by reducing the amount of wave power reaching the coastlines [2]. Designing a wave farm with the objective of maximizing coastal protection involves optimizing the layout and the location decision. This research stream has been introduced to literature recently with a few articles addressing the optimization aspect [2, 192].

Accommodation - Accommodation strategies involve modifying the physical design to enable the structure or land use to remain in place. Examples include floodable developments, floating and elevated structures, and enhancing urban drainage capacity [66, 71, 109, 172, 195, 208]. For instance, the Netherlands has implemented a policy called "Room for the River" to manage periodic flooding along all major Dutch rivers [189]. This flood risk management program, launched in response to the devastating floods of 1993 and 1995, aims to provide more space for rivers and protect the country against flooding. It includes a combination of measures such as creating bypasses, widening rivers, and lowering floodplains. Additional accommodation measures involve retrofitting buildings with flood-resistant features such as elevated electrical systems, waterproofing, and improved drainage systems, which effectively mitigate flood damage. These measures often exhibit a system-specific nature, particularly at the operational level. A comprehensive discussion of these measures will be provided in the following section, where we examine various infrastructure systems.

Retreat - Retreat involves withdrawing from areas where protection or accommodation measures are ineffective or inefficient. This can occur voluntarily, with incentives, or gradually over time. Communities can plan for an eventual retreat from barrier islands and high-hazard coastal zones while cautiously investing in assets, considering their expected lifespan and projected inundation [47, 87, 151, 199]. It's important to emphasize that effective communication about retreat strategies is challenging. The choice of language to convey adaptation plans can significantly influence how communities respond to proposals. As such, alternative terms, such as "planned relocation" or "managed realignment," are commonly used [198]. Communities exploring managed retreat usually consider mechanisms such as home buyout programs, rolling easements, and land swaps [9].

3 Decision-Making Approaches for Adaptation

Adaptation investment decisions are typically made based on *prediction-first approaches* (also referred to as predict-then-act), where inferences gathered from future predictions inform policy choices. The goal in such decisions is to maximize the expected utility produced by a system [4, 88, 123, 148, 165, 239]. If the probability distributions are reliable and comprehensive, then decision-makers can exploit the models exhaustively to achieve stochastically optimal outcomes. However, if processes are changing unpredictably, or if important factors have to be considered but are beyond the decision-maker's knowledge or control in the meantime, then deep uncertainty is involved and the traditional predict-then-act strategies will probably fail in the long-term [150].

The limitations of these traditional decision-making approaches for valuing climate adaptations have been recognized in research and practice. Consequently, alternative decision-making strategies such as *robust and adaptive decision-making methods* are proposed to better incorporate deep uncertainty. Unlike the predict-then-act approaches, robust strategies employ a policy-first approach [123], where a set of potential policy options are identified and their robustness under a broad range of possible futures is assessed. Therefore, instead of optimizing investment decisions for one specific predicted scenario, optimization is achieved across myriad scenarios [29, 30].

Another approach, *adaptive decision-making*, involves the identification and assessment of flexible and adaptable strategies that can dynamically adjust decisions based on changing conditions or feedback [59]. Several schemes fall under the adaptive decision-making approach including Dynamic Adaptive Planning (DAP) and real options analysis [118, 227]. These various modeling approaches and their deployment in adaptation decision-making are discussed in the following subsections.

Before discussing these approaches in detail, we first

3.1 Prediction-first Approaches

In prediction-first decision-making approaches, the decision-making strategy starts by predicting the future sea levels and the associated risks. The aim is to analyze impacts and quantify damages associated with future climate change. In response to the projected impacts, decision-makers identify a set of potential adaptation strategies and evaluate them with respect to predefined social, economic, or environmental indicators. In this approach, valuing investment projects is widely handled by *cost-benefit analysis* [51, 65, 72, 78, 118, 119, 245], *multi-criteria analysis* [31, 155, 196], and *deterministic or stochastic optimization* [51, 72, 78, 133, 148, 160, 216, 220, 239, 242].

In cost-benefit analysis, given the estimated impacts of a predicted sea-level scenario, a variety of adaptation potentials are identified, valued, and evaluated against the base do-nothing scenario according to their respective ratios of costs to benefits [70]. Multi-criteria and index-based analysis involve ranking a set of indicators based on weights that are specified by the decision-makers. For example, in planning adaptation options for the community of Delta, in Metro Vancouver, Canada, under the projection of 1.2 m of sea-level rise, Barron et al. [31] evaluated a set of potential adaptation options based on key indicators and their respective weighted importance, such as agricultural land area protected or unprotected under a particular option, length of roads protected or unprotected, the cost of implementation of each adaptation option, etc. Multi-criteria analysis does not generally decide on the optimal or the best decision, rather, fosters informed decision-making by assessing the benefits of a variety of adaptation options and their combinations.

Table 1: Examples of Optimization-based Adaptation Decision Models following prediction-first approaches

Year	Ref.	Sector	Objective	Decision Variables	Modelling Approach	Solution Methodology
1999	[239]	UD	Min. Flood Volumne	Pumping Rates	FLC	GA
2003	[148]	WS	Max. Total Pumping	Pumping Rates	MINLP	SQP
2004	[165]	WS	Max. pumping rates from each well, Min. distance between stagnation points and the coastline location	Pumping rates and well locations	MOP	GA
2008	[129]	ECO	Max. difference between total benefits and costs of adaptation	Beach replenishment operations (optimal beach width)	CBM + DP	DP
2010	[88]	Others	Min. Cost and Max. Safety	Flood diversion planning	Inexact FCC two-stage MILP	-
2013	[51]	Others	Min. investment and damage costs	Timing and height of dikes	MINLP	ICP
2014	[220]	Others	Min. investment and damage costs	Dike height and timing of upgrade	SO	DP
2016	[160]	UD	Min. flood damage (maximum water depth)	Pumping working depths and weir crest height	Single-Objective LP	E-PSO
2018	[231]	UD	Min. flood volume and rehabilitation costs	Pipe sizing	MOP	GA
2019	[159]	UD	Min. installation and flood damage costs	Pipe and storage tank sizing	MOP	GA

WS: Water Supply, UD: Wastewater and Urban Drainage, ECO: Ecosystems, FLC: Fuzzy Logic Control, GA: Genetic Algorithm, MINLP: Mixed Integer Non-Linear Programming, SQP: Sequential Quadratic Programming, MOP: Multi-Objective Optimization, CBM: Control-Based Models, DP: Dynamic Programming, FCC: fuzzy chance-constrained Model, MILP: Mixed-Integer Linear Programming, ICO: Impulse Control Programming, SO: Stochastic Optimization, LP: Linear Programming, E-PSO: Extraordinary particle swarm optimization algorithm

Furthermore, optimization is a key tool utilized in valuing adaptations. It involves evaluating adaptation strategies based on specific scenarios of future SLR. Deterministic optimization considers a particular SLR scenario, while stochastic optimization takes into account the discrete probabilities of various scenarios. The objective of the optimization is to minimize costs and/or flood volume [62, 159, 231], or maximize benefits[148, 165]. Based on our examination of the pertinent literature and the optimization techniques outlined in Table 1, we find that the implementation of optimization approaches has been widely embraced for making SLR adaptation decisions in the context of water supply and wastewater resources. Because the analytical traditional methods and deterministic optimization fail to account for the inherent uncertainty of future conditions, some articles consider optimization under probabilistic uncertainty approaches including stochastic optimization [220, 242, 244], dynamic programming [129], and chance-constrained optimization [88]. In these optimization problems, it is almost always assumed that the probability distribution of the random parameters is known. For example, a probability distribution for the rise in water levels is introduced to model flooding uncertainty when making adaptation decisions about dike heights [220].

3.2 Robust Decision Approaches

Robust Decision-Making (RDM) combines scenario generation and Exploratory Modeling and Analysis (EMA) to stress test strategies over myriad plausible paths into the future. The performance of decision strategies is then evaluated across these scenarios in order to identify the conditions – or trigger points - under which candidate strategies might fail to meet the goals [29]. Evaluating the performance of various strategies can be performed using optimization, machine learning, or using simulation-based optimization. Combined simulation-optimization (S/O) schemes have long been recognized as a valuable tool in water resources management such as coastal groundwater management [4, 177], reservoir and detention facilities management problems [74, 241], and saltwater-intrusion management [68].

Unlike Stochastic Optimization (SO), Robust optimization (RO) does not assume that probability distributions are known a priori. Instead, RO assumes that the uncertain data resides in an "uncertainty" [86] or "ambiguity" set [40]. Several approaches are proposed in the SLR-adaptation literature for generating the uncertainty set. The State of the Worlds (SOWs) approach proposed by Garner et al. [79] employs parameters that represent future states of the world with a distribution of possible values. Drawing a sample from each parameter's distribution represents a single state over which the model is evaluated. Repeating this process provides a series of outcomes constituting the uncertainty set. Another strategy developed by Brekelmans et al. [48] involves combining the regret approach with a finite set of scenarios, where each scenario represents an instance of all uncertain model parameters. In this approach, the adaptation decision has to be made before the uncertain parameter value becomes known. Once the actual value is known, a measure of the quality of the decision can be obtained by calculating the regret. Robust optimization can then be performed by choosing the approach that minimizes the average or the maximum regret over all scenarios. Table 2 presents a collection of articles relying on robust optimization to derive adaptation solutions.

Table 2: Examples of Optimization-based Adaptation Decision Models following Robust Decision-Making Approaches

Year	Ref.	Sector	Objective	Decision Variables	Modelling Approach	Solution Methodology
2009	[68]	WS	Max. pumping from production wells, Min. extraction from barrier wells	Pumping rates for each well	S/O – Multi-Objective RO	EMO / GA
2011	[4]	WS	Min. total cost	Well depths, locations, and abstraction/recharge rates	S/O - MLP	GA
2012	[48]	Others	Min. Regret	Height of each dike segment in a non-homogeneous dike ring, timings of dike segment heightening	MINLP / RO	Divide-and-Concur Algorithm
2012	[74]	WS	Min. Flood damage	Reservoir annual rule curves	S/O - MLP	DEO
2013	[130]	AGRI	Max. the farmer's utility in crop production relative to the Certainty Equivalent (CE)	Irrigation and fertilization strategies	S/O - MLP	GA
2016	[128]	others	Min. damage, causalities, and costs	Adaptation policy actions	S/O - Multi-Objective RO	GA
2017	[177]	WS	Min. SWI / failure	Groundwater extraction rates	S/O - MNLP	Continuous ACO
2017	[80]	WS	Min. flood volume	Release schedule for connected reservoirs	Multi-stage RO	ADR
2018	[79]	Others	Min. investment and damage costs	Dike heightening timings	Multi-objective RO / DPS	Master-slave BORG multi-objective EA
2019	[241]	UD	Min. flood volume	Value of gate openings	S/O - MLP	DEO
2019	[248]	UD	Min. total costs	Storage tank sizes	S/O - SBO	GA, ADR

WS: Water Supply, UD: Wastewater and Urban Drainage, ECO: Ecosystems, S/O: Combined Simulation-Optimization, EMO: Evolutionary multi-objective optimization, RO: Robust Optimization, GA: Genetic Algorithm, MLP: Mathematical Linear Programming, MINLP: Mixed Integer Non-Linear Programming, DEO: Differential Evolution Optimization, ACO: Ant Colony Optimization, DPS: Direct Policy Search, EA: Evolutionary Algorithm, SBO: Surrogate-Based Optimization

Besides optimization and simulation-based optimization techniques, the Info-Gap (IG) theory is another robust decision-making approach that is used in adaptation decision-making literature. Info-Gap (IG) decision theory is a non-probabilistic decision theory for prioritizing alternatives and making choices and decisions under deep uncertainty. An "info-gap" is the disparity between what is known and what needs to be known for a responsible decision [38]. Decisions made under IG theory have high robustness, meaning that they achieve the goals of the adaptation action under a wide variety of unknown futures. Unlike the Min-Max and worst-case analysis that might be unnecessarily costly by considering the worst-case situation, the IG theory targets the worst tolerable outcome, and the decision is made such that the outcome of that decision is no worse than the pre-identified worst tolerable consequence [39].

In the context of SLR adaptations, very few articles employ the IG theory in making adaptation decisions. In one of the few studies, Hine et al. [99] explore the use of IG approach to analyze the sensitivity of flood management decisions to uncertainties in flood inundation for some catchment sites in the UK. The authors consider three flood defense options and in each case, construction cost is compared to the benefits, measured in terms of reduction in expected annual flood damage relative to a base do-nothing scenario. In the context of adapting water supply systems, Matrosov et al. [153] applied the IG framework to London's water resource system expansion problem. By integrating IG framework with multi-criteria analysis, their proposed method helps identify the most robust strategy among 20 proposed water supply infrastructure portfolios under a highly uncertain future of hydrological inflows, water demands, and energy process. In another study, Korteling et al. [124] utilize the IG theory to quantitatively assess the robustness of various supply and demand side management options coupled with multi-criteria analysis. Their approach shift the focus away from reservoir expansion decisions to integrated strategies that focus on managing the demand side actions such as rainwater collection and grey water reuse.

3.3 Adaptive Decision Approaches

Adaptive planning also referred to as dynamic planning, is well-suited for decisions that can be revisited over time [123, 131]. A variety of approaches fall under this decision-making strategy and many of them are applied in the SLR-adaptation context, in particular water management decisions. Adaptive decision-making strategies include Dynamic Adaptive Planning (DAP), Adaptation Pathways (AP), Adaptation Tipping Points (ATP), Dynamic Adaptive Policy Pathways (DAPP), and Real-Options Analysis (ROA). The main idea of adaptive decision-making relies on specifying a set of objectives and constraints, based on which an initial short-term plan is designed, and a framework to guide future, contingent actions is established [150]. Although these strategies share the same concept, they vary in terms of how they identify different climate paths and trigger points, where the current plans will no longer remain feasible and there will be a need to switch to an alternative adaptation path.

In the extant literature, some work classifies the above-mentioned strategies as partially overlapping and complementary and as such recommends their adoption independently of one another [81]. Others synthesize them under the Dynamic Adaptive Policy Pathways (DAPP) [91, 226]. DAPP integrates two adaptive planning approaches; Dynamic Adaptive Planning [228] and Adaptation Pathways [92]. Also central to the approach is Adaptation Tipping Points [127]. In general, DAPP comprises the following steps: (1) outline the scope and objectives of adaptation and characterizes uncertainties; (2) utilize these uncertainties to generate future scenarios to identify vulnerabilities and opportunities, which elucidates if and when policy actions are needed; (3) identify the possible actions that can be employed as the basic building blocks for the adaptation pathways. In subsequent steps, the performance of all possible pathways is assessed in light of the predefined objectives, and the adaptation tipping point (ATP) is determined. Once a set of actions is proven to be adequate, adaptation pathways are designed such that each pathway is a combination of several actions. Subsequently, one or more pathways can be identified as the initial basic adaptation plan. Once contingency actions and the trigger points for each contingency action are specified, monitoring for these points begins. The process of integrating a monitoring system and prespecifying contingent responses when certain trigger values are reached is tackled by Dynamic Adaptive Planning (DAP).

Dynamic Adaptive Planning (DAP), also known as Adaptive Policy-making, was first outlined by Walker [228], and further developed by Kwadijk [127]. DAP differs from other decision-making approaches in that it adds flexibility to the robust decision-making plan through the integration of the monitoring system. The monitoring system consists of signposts and triggers. Signposts specify the types of information and variables that should be monitored to show (1) whether the initial plan is currently achieving its goals and/or (2) whether the vulnerabilities identified earlier are hindering the plan from achieving its goals in the future. Triggers are the critical signpost levels or events signifying that contingent actions should be taken to ensure the initial plan remains on course and thus, continues to achieve its specified goals. Contingent actions are taken in response to vulnerabilities and opportunities. The main distinction between the different adaptive plans is how vulnerabilities are identified. Under DAP, vulnerabilities are identified by analytical tools such as exploratory modeling, scenario discovery, etc.

Adaptation Tipping Points (ATP) and **Adaptation Pathways (AP)** – Both AP and ATP focus explicitly on the timing of the contingency actions. Originally, the ATP approach was developed by Kwadijk [127] in response to the need for updating the Dutch water management plan as new climate scenarios were released. The objective was to develop a planning approach that is less dependent on the climate scenarios available at the time of designing the plan. Therefore, adaptation tipping points are defined by answering the question "Under what conditions will a given plan fail?" instead of focusing on a finite set of scenarios that might occur in the future. To reach a tipping point, a pathway is required. Therefore, the Adaptation Pathway (AP) generates an overview of the different routes leading to such points in the future.

Applying the DAPP in developing adaptation strategies for future SLR has been studied with few practical applications. For example, Kwakkel et. al [128] attempt to develop an adaptation strategy from over 20 policy options integrating various adaptation measures such as heightening the dikes, strengthening the dikes, making room for rivers, and building additional embankments around cities and houses on stilts. Following the concept of the DAPP, these options can be combined into pathways that are executed simultaneously or in sequence. The authors employ multi-objective robust optimization approach to find the optimal adaptation pathways for a hypothetical case study referred to as the "Waas" which is based on the Waal, a river reach in the Rhine Delta of the Netherlands. Using an alternative approach, Manocha and Babovich [146] rely on the real-options valuation method to compare all possible pathways and decide on the preferred baseline (or initial) pathway for the Waas case. Other studies provide adaptation solutions to flood risks in Singapore [147], the Netherlands [93], and Australia [179].

Table 3 highlights the use of OR-based tools for developing decision-making models to adapt infrastructure systems to the risks of SLR. One notable gap identified is the lack of integrated adaptation planning and participation of multiple stakeholders in the decision making process. Effective adaptation planning necessitates a comprehensive approach that considers social, economic, and environmental dimensions. Unfortunately, most reviewed articles fail to adequately address this integration, potentially leading to suboptimal decision-making processes. Additionally, insufficient stakeholder involvement inhibits the incorporation of diverse perspectives and priorities, thereby impeding the creation of robust, equitable, and socially just adaptation strategies. Furthermore, the existing literature predominantly concentrates on the risks of flooding stemming from SLR, disregarding other crucial hazards. While flooding is undoubtedly a significant issue, it is crucial to acknowledge and address additional risks such as saltwater intrusion, inland flooding, and coastal erosion. These risks have far-reaching implications for the functionality and resilience of vital infrastructure systems. Neglecting their impacts can result in inadequate adaptation measures and increased vulnerability of infrastructure systems to SLR.

Another notable limitation in the literature is the overwhelming reliance on prediction-first approaches to develop decision-making strategies. While prediction is an important aspect of understanding future risks and making decisions regarding the future, it should not be the sole basis for decision-making. The literature would benefit from incorporating robust and adaptive decision-making frameworks that account for deep uncertainties and consider more robust adaptation decision models.

In the next section we delve deeper into these limitations and present a more detailed review on system-level adaptations with particular focus on critical infrastructure systems such as transportation, water and wastewater supply, power generation and transmission, and agriculture.

4 Sector-Based Adaptation Approaches

This section offers a comprehensive review of the existing literature that delves into the challenges associated with decision-making in the context of the previously mentioned adaptation strategies. The focus is specifically on various infrastructure systems vital for addressing fundamental human needs and widely prevalent in societal functioning. The selected systems include transportation, water supply, wastewater and urban drainage, power generation and transmission, as well as farming and agriculture infrastructure. A notable emphasis is placed on OR/OM models and tools to illuminate their role in addressing decision-making challenges within these critical infrastructure domains.

Table 3: Overview of research papers addressing OR-based adaptation decision making models

Year	Ref	Sector								Adaptation Strategy			Integrated Impact Assessment	Stakeholder Involvement	Integrated Adaptation Planning	Decision-making Approach			Decision-making Methodology							Risks			Country	Uncertainty
		Transportation	Wastewater and Urban Drainage	Water Supply	Power Generation and Supply	Farming and Agriculture	Coastal Ecosystems	Real Estate	Others	Protection	Accommodation	Retreat				Prediction-first Approach	Adaptive Decision-Making	Robust Decision-Making	Agent-based/Monte-Carlo Simulation	System Dynamics	Optimization	Cost-Benefit Analysis /NPV	Real Options Assessment	Multi-Criteria Analysis/AHP/	Index-based Methods	Coastal/Inland Flooding	Salt-water Intrusion	Coastal Erosion		
1997	[245]							✓		✓						✓						✓				✓		✓	USA	✓
1997	[205]								✓	✓						✓			✓							✓			Netherlands	✓
1999	[239]		✓								✓					✓					✓					✓			Japan	
2003	[148]			✓							✓					✓					✓							✓	Greece	
2004	[165]			✓						✓						✓					✓							✓		
2008	[129]						✓	✓		✓						✓			✓		✓							✓	USA	
2009	[68]			✓							✓							✓			✓						✓		India	
2010	[88]								✓		✓				✓	✓					✓					✓				✓
2010	[99]							✓		✓	✓	✓			✓			✓				✓				✓			UK	✓
2011	[4]			✓							✓							✓			✓						✓		USA	✓
2012	[48]								✓	✓								✓			✓					✓			Netherlands	✓
2012	[31]	✓				✓	✓	✓	✓	✓	✓	✓		✓		✓								✓		✓			Canada	✓
2012	[74]			✓							✓							✓		✓	✓					✓			Canada	
2013	[196]								✓	✓	✓	✓		✓		✓				✓				✓		✓			Australia	✓
2013	[51]								✓	✓						✓					✓					✓			Netherlands	✓
2013	[102]		✓								✓						✓				✓					✓			Taiwan	✓
2013	[133]		✓								✓					✓					✓					✓			China	✓
2013	[124]			✓							✓							✓						✓		✓			UK	✓
2013	[130]					✓					✓					✓					✓					✓			Switzerland	✓
2013	[153]			✓							✓							✓						✓		✓			UK	✓
2013	[64]					✓					✓					✓					✓								India	
2014	[141]	✓														✓						✓				✓			USA	
2014	[119]								✓	✓						✓			✓			✓				✓			Netherlands	✓
2014	[72]								✓	✓								✓	✓		✓	✓				✓			Netherlands	✓
2014	[220]								✓	✓						✓					✓					✓			Netherlands	✓
2014	[243]		✓								✓							✓	✓		✓					✓			South Korea	✓
2014	[235]		✓								✓						✓				✓					✓			Taiwan	✓
2015	[216]								✓	✓						✓					✓					✓			Netherlands	✓
2015	[229]	✓								✓	✓	✓			✓		✓									✓			USA	
2015	[244]		✓								✓						✓				✓					✓			South Korea	✓

Table 3: Overview of research papers addressing OR-based adaptation decision making models (Cont.)

Year	Ref	Sector								Adaptation Strategy						Decision-making Approach			Decision-making Methodology							Risks			Country	Uncertainty
		Transportation	Wastewater and Urban Drainage	Water Supply	Power Generation and Supply	Farming and Agriculture	Coastal Ecosystems	Real Estate	Others	Protection	Accommodation	Retreat	Integrated Impact Assessment	Stakeholder Involvement	Integrated Adaptation Planning	Prediction-first Approach	Adaptive Decision-Making	Robust Decision-Making	Agent-based/Monte-Carlo Simulation	System Dynamics	Optimization	Cost-Benefit Analysis /NPV	Real Options Assessment	Multi-Criteria Analysis/AHP/	Index-based Methods	Coastal/Inland Flooding	Salt-water Intrusion	Coastal Erosion		
2016	[128]					✓		✓	✓	✓	✓	✓	✓		✓		✓	✓			✓					✓			Netherlands	✓
2016	[62]		✓								✓						✓				✓					✓			Portugal	
2016	[160]		✓								✓					✓					✓					✓			South Korea	✓
2016	[155]								✓	✓	✓	✓		✓		✓								✓		✓			Greece	
2016	[146]								✓	✓	✓		✓		✓		✓						✓			✓			Netherlands	✓
2017	[177]			✓							✓							✓	✓		✓						✓		Iran	✓
2017	[230]		✓								✓					✓					✓					✓			China	
2017	[246]		✓								✓					✓					✓					✓			Singapore	✓
2017	[80]			✓							✓							✓			✓					✓			Canada	✓
2018	[65]	✓								✓		✓					✓					✓	✓			✓			UK	✓
2018	[79]									✓				✓				✓			✓					✓			USA	✓
2018	[210]								✓		✓			✓				✓				✓				✓			USA	✓
2018	[93]			✓						✓	✓			✓	✓		✓				✓					✓			Netherlands	✓
2018	[147]		✓								✓						✓				✓		✓			✓			Singapore	✓
2018	[108]		✓								✓						✓				✓					✓			Iran	✓
2018	[231]		✓								✓					✓					✓					✓			China	
2018	[238]		✓								✓					✓					✓					✓			China	✓
2019	[241]		✓								✓							✓			✓					✓			Iran	
2019	[159]		✓								✓				✓	✓					✓					✓			Columbia	
2019	[250]		✓								✓							✓			✓					✓			China	✓
2019	[232]		✓								✓						✓						✓			✓			China	
2020	[195]		✓								✓						✓						✓			✓			USA	
2020	[182]			✓											✓			✓	✓								✓		USA	✓
2022	[208]				✓					✓	✓				✓	✓					✓					✓			USA	

4.1 Transportation Infrastructure

A multitude of strategies have been developed to adapt transportation systems to SLR. These strategies primarily focus on enhancing the resilience of transportation networks, such as elevating roads and rail levels, increasing redundancy within the network, and implementing changes in land use to reduce the vulnerability of exposed areas. In the context of road transportation systems, strategic investments and adaptation measures often include the rehabilitation or retrofitting of network components to bolster their structural integrity and enhance their ability to withstand disruptions. This may involve the implementation of various protective measures, including the construction of seawalls, raising transportation elements, and improving road drainage, as frequently seen in many communities (National Research Council, 2010). In addition to these conventional adaptation approaches, there is growing interest in innovative strategies that incorporate green infrastructure as a sustainable solution for accommodating transportation infrastructure and mitigating future climate change-related risks [83]. Another stream of research focuses on resilience of logistics and supply chain systems [110] that significantly depend on the transportation networks [111].

Protection – Protection strategies involve both hard and soft measures. Construction of levees and flood walls to prevent wave overtopping and flooding of roadways are examples of hard protection measures [139, 229]. Additionally, protecting critical bridge elements such as bridge foundations and bridge approach embankments could be done by installing armoring material such as riprap [120, 135, 229], or tying down bridge decks [162]. Soft protection measures employed in this context include construction of berms and wetland restoration. Inundation of roads from rising tides could be prevented with a berm along the road perimeter and near off and on ramps, in addition, the growth of wetlands helps damp wave actions, thus reducing inundation of roadways [229].

Accommodation– Accommodating transportation infrastructure can be achieved by elevating critical system elements including roads, toll plazas, electrical systems, and critical road operations above the projected inundation elevations [35, 161]. Other adaptation options consider implementing changes in the network architecture, pavement structure, and materials with the goal of meeting or exceeding certain performance thresholds as exemplified by Knott et al. [122]. The authors evaluate various pavement structures to determine adaptation feasibility and costs to maintain the designed pavement service life in the face of the rising groundwater. Managerial and operational strategies such as temporary closures of inundated road sections, detour planning, and alternate crossing mode planning such as increased reliance on ferry services as a backup for disrupted network, are among strategies for adapting transportation networks to SLR impacts [161, 229].

Additionally, designing against future scour for roads and bridge foundations is among the most important adaptation strategies implemented in practice. To achieve this, the design and construction of roads, bridges, and causeways generally adhere to scour design standards for hydraulic loads on the substructure for 100-year flooding events [67]. Furthermore, enhancing drainage capacity would also increase the resilience of the transportation network in case of any disruptive events. For example, in developing their dynamic decision model for adapting the San Francisco-Oakland Bay Bridge approach, Wall et al. [229] consider monitoring the stormwater drainage levels. Also, [35] suggest installing additional pump stations to increase the drainage capacity of the roads as a potential adaptation action in the city of Miami Beach.

Beyond the physical transportation infrastructure, a critical concern for the OM society involves ensuring the resilience of supply chains to climate-induced risks. Ghadge et al. [82] provide a review of literature focusing on this particular aspect. They report that, although all sectors are expected to be impacted by the climate change-related stressors, only limited sectors, namely food and transportation, are studied comprehensively from a general sustainability perspective. The authors underscores the importance of diversifying sourcing channels as a fundamental strategy in managing climate change risks. This involves reducing reliance on single sources by cultivating alternative procurement avenues, mitigating disruptions stemming from SLR and climate-induced impacts on specific locations and enhancing overall supply chain stability. This approach, complemented by proactive vulnerability and risk identification [158], can enable an adaptable framework to navigate the challenges posed by rising sea levels, ensuring the uninterrupted flow of global trade and commerce.

Typically, combining multiple strategies enhances resilience against future risks, taking into account financial constraints. As shown in Table 4, in contrast to the absence of integrated risk assessment demonstrated in Table 3 above, nearly all the examined articles on adapting transportation infrastructure systems have considered an inclusive adaptation planning approach.

Table 4: Overview of research papers addressing adaptation of transportation infrastructure

				Protection		Accommodation						Methodology			
Ref.	Year	Country of Case Study	SLR-Risks	Hard Measures	Soft Measures	Retrofit/Elevation	Enhancing Drainage	Redesign Network	Operational/ Maintenance	Green Infrastructure	Retreat / Relocation of Components	Optimization	Process Modeling	Agent-based Simulation	Economic Analysis
2011	[161]	USA	Flooding	✓		✓	✓				✓				✓
2012	[139]	USA	Flooding	✓		✓					✓		✓		
2012	[162]	USA	Flooding + PPT	✓		✓					✓		✓		✓
2014	[20]	USA	Flooding			✓									✓
2014	[76]	USA	Flooding			✓									✓
2014	[140]	USA	Flooding	✓		✓			✓		✓				✓
2015	[229]	USA	Flooding	✓	✓	✓	✓		✓		✓	✓			
2017	[21]	USA	Flooding + PPT	✓			✓				✓	✓			
2017	[26]	Austria	Flooding				✓		✓	✓					✓
2018	[35]	USA	Flooding			✓	✓							✓	
2018	[122]	USA	Inland Flooding			✓									✓
2019	[164]	USA	Flooding + PPT	✓								✓			
2019	[233]	UK	Flooding + PPT			✓	✓		✓						✓
2020	[134]	USA	Flooding	✓		✓						✓			✓
2020	[211]	USA	Flooding	✓									✓	✓	
2020	[218]	India	Flooding + PPT			✓		✓	✓		✓		✓		

PPT: Precipitation causing fluvial (inland) flooding

4.2 Water Supply Infrastructure

Adapting water supply networks to future climate risks involves increasing freshwater availability and minimizing water contamination by limiting saltwater intrusion (SWI). While extensive research has focused on studying saltwater intrusion in coastal aquifers, only a few models have been developed to manage them. Measures to control saltwater intrusion include: (1) reducing abstraction rates, (2) relocating abstraction wells, (3) using subsurface barriers, (4) implementing natural and artificial recharge, (5) abstracting saline water, and (6) combining injection and abstraction systems [213].

In addition to mitigating saltwater intrusion, other measures are considered to ensure a sufficient freshwater supply in case of network disruptions. These measures include constructing redundant tunnels, exploring alternate water supplies and storage methods, such as expanding the groundwater system, implementing groundwater banking of surface water, and desalinating saline water [194]. In this section, we discuss various measures, both documented in the literature and implemented in practice, to accommodate the water supply system for anticipated risks associated with SLR.

Protection – Under the protection approach, subsurface barrier walls – also known as cutoff walls – are considered to prevent the inflow of seawater into the freshwater basin [3]. Barrier walls are one of the most effective methods for protecting freshwater basins by facilitating the retreat of saltwater intrusion. However, a critical decision in constructing an effective barrier wall is where to locate it and how deep it should be, also known as embedment depth [143, 17].

Another type of underground physical barrier that controls saltwater intrusion is the subsurface dam. This dam blocks the flow of groundwater to and from the sea. Because these dams have an undesired effect by blocking pollutants on the inland side of the dam, extant research proposes using them at the minimum effective height that prevents saltwater intrusion while minimizing the adverse environmental impact [52]. Currently, there are around 15 underground dams constructed in Japan, seven of which are explicitly built to control saltwater intrusion into aquifer systems [17]. To maximize the dam's efficiency in controlling saltwater intrusion, several decisions need to be made, including the effective dam height, distance from the saltwater boundary, and head difference [52]. These approaches are illustrated in Figure 2.

Accommodation – Accommodating the existing water supply system to future risks due to SLR, in particular saltwater intrusion, often focuses on the freshwater supply side, either by controlling saltwater encroachment into the aquifers and basins or by storing freshwater and considering a diversity of water sources such that a particular quantity of freshwater is maintained. In controlling saltwater intrusion, in addition to physically protecting the aquifers and basins, accommodation approaches generally fall into two categories: *hydrodynamic control* and *extraction wells*. Hydrodynamic control refers to projecting the hydraulic gradient of the system seaward, therefore repositioning the freshwater-saltwater boundary at a distance from the production wells. Hydrodynamic control includes methods such as changing current pumping schedules, relocation of wells, aquifer recharge, and creation of hydrodynamic barrier and pumping trough. Whereas extraction wells function by extracting seawater before it reaches the production wells, or by de-

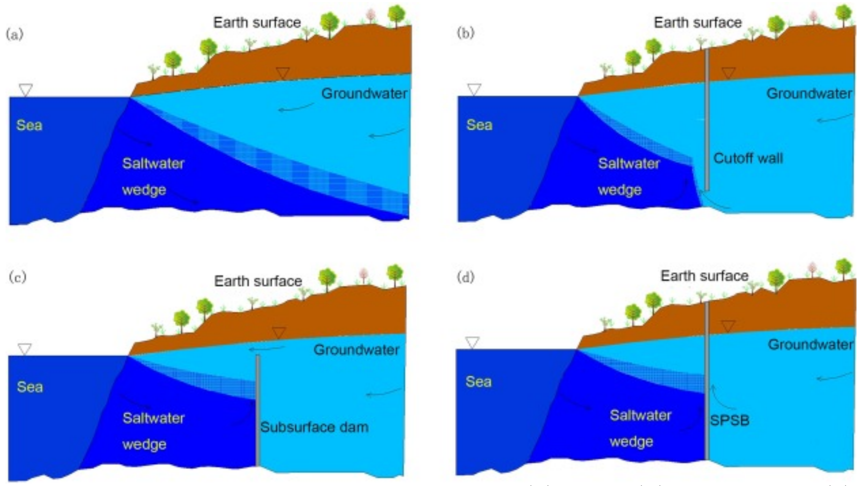

Figure 2: Schematic diagrams of SWI and physical barriers (a) SWI; (b) Cutoff wall; (c) Subsurface dam; (d) Semi-pervious subsurface barrier (SPSB). [52]

ploying a combination of extraction and injection wells, where extraction wells withdraw saltwater while injection wells recharge freshwater [202]. Throughout the remainder of this sub-section, we briefly discuss these various accommodation approaches.

Managed Aquifer Recharge (MAR), or artificial recharge has been effectively adopted during the past 60 years on a global scale. It refers to a variety of methods that are used to maintain and secure groundwater systems under future climate stressors [69]. There are several methods addressed under the MAR scheme, some are meant to create a hydraulic ridge and therefore control the saltwater intrusion, such as the recharge wells. Other methods help maintain the quantity of freshwater by considering alternate sources of freshwater that are recharged to the aquifer, such as streambed channel modification, bank filtration, and water spreading that are deployed to provide diverse sources of supply.

The installation of recharge wells (Figure 3) is among several strategies proposed to minimize saltwater intrusion in coastal aquifers and it is the most pragmatic and cost-effective measure to implement [137]. The main objective of freshwater injection through recharge wells is to produce a hydraulic barrier preventing the saltwater from further encroachment inland [143]. This requires a line of recharge wells that are located landward from the toe of the saltwater-freshwater interface and at a distance that is far enough from the toe to provide enough space for seaward flow. The development of recharge well systems is commonly used in India, Israel, the USA, Northern Europe, and Australia. There are many examples of the successful application of this strategy in the US, including the West Coast Barrier, the Dominguez Gap Barrier, and the Alamitos Gap Barrier installed at Los Angeles County and Orange County in California [137].

Several optimization models were developed for the efficient management of coastal aquifers through recharging wells in order to control saltwater intrusion into the aquifer. The general objective of is to maximize the total pumping rate from a number of wells and identify the optimal pumping schedule [23, 165]. In general, two sets of constraints are considered in this problem. The

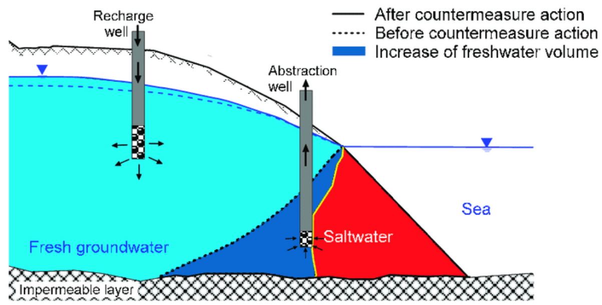

Figure 3: A generalized sketch of an abstraction-recharge barrier system [103]

first one, the tow constraint, ensures protecting the wells from saltwater intrusion by not allowing the tow of the interface to reach the wells. The second constraint, referred to as the potential constraint, ensures protecting the wells by maintaining a potential flow at the wells that is larger than the toe potential [148]. Comprehensive reviews of optimal management of saltwater intrusion can be found in [23, 63].

Another adaptation strategy involves recovering freshwater from seawater using reverse osmosis membranes, a process known as seawater desalination. This approach is highly favored in southeast Florida [44] and finds applications in the western Belgian coastal plain [222]. In these regions, artificial recharge projects integrate into the water cycle, with extracted water serving users and their wastewater purified for recharging the dunes. Decisions in this context include optimizing depths, locations, and abstraction/recharge rates from and to the wells to minimize total construction and operational costs while maximizing freshwater desalination rates [4].

Unlike the recharge wells strategy, the seawater extraction approach, also known as the negative barriers strategy, involves a line of pumping wells designed to control the withdrawal of water from the freshwater-saline water interface. These wells play a crucial role in extracting intruding seawater through trough wells, draining it back to the sea, or desalinating it for recharge into the freshwater basin or irrigation purposes [113, 203]. In general, extraction barriers induce a drop in the piezometric head near the coast, enhancing the saltwater hydraulic gradient and thereby protecting the aquifer from saltwater intrusion. However, due to the seaward gradient, this approach may result in the extraction of more freshwater than saltwater, making it unsuitable as a permanent strategy. To address this challenge, one proposed method involves the use of a double pumping barrier system with two extraction wells: an inland well for pumping freshwater and a seaward well for pumping saltwater. This configuration creates a low-velocity zone between the two abstraction zones with a horizontal gradient, effectively protecting and maximizing the pumping of the freshwater production well [138, 173, 223].

In managing the abstraction of groundwater, the typical objective is to optimally schedule the extraction of freshwater from various pumping locations (production wells) for different time periods in a way that no further intrusion of seawater is imposed while maximizing groundwater extraction [116, 177, 204, 209]. Other objectives include minimizing the draw down, amount of water, seawater intrusion and/or minimizing the pumping cost. In order to address any of these objectives, one of two decisions, or both, needs to be made: pumping rates for each well [185] and optimal well numbers and locations [149].

Effective freshwater storage and reservoir management is also crucial for accommodating risks caused by SLR. The efficient utilization of existing reservoir storage under changing climatic conditions begins with estimating the runoff, which serves as the inflow into the reservoir system. This estimation is typically done through hydrologic modeling. The modeled reservoir inflows then become inputs for optimization algorithms that determine reservoir operating rules, known as reservoir rule curves. These curves represent potential adaptation strategies to changing climatic conditions [74]. Identifying the rule curves for reservoir operation is a dynamic process for two main reasons. Firstly, there is a variation in hydrological conditions, including reservoir inflows affected by rising seas. Secondly, uncertainty arises from changes in water allocation to downstream areas due to factors such as population growth and land-use demand changes [114].

The rule curves serve as a critical reference in obtaining the optimum volume of water stored in the reservoir at any time interval. This optimization extends to the allocation of water released for various purposes in different areas, with the aim of minimizing water shortages downstream. In cases where reservoirs are interconnected, designing an optimal release schedule for this interconnected system becomes challenging. Such cases involve decisions related to various water control structures within a given time period, all while considering the dynamical structure and topology of the system. Multiple optimization models are presented in the literature addressing the reservoir operations management problem. For further exploration, interested readers can refer to some of these publications [88, 74, 114, 80, 182, 84].

As the risks associated with SLR threaten the stability of water supply infrastructure, the existing systems may struggle to function adequately amidst increasing demands. Therefore, alongside accommodating the existing infrastructure, another approach is to consider capacity expansion to maintain the resilience of water supply operations under future risks. Capacity expansion involves constructing new storage facilities and increasing the capacity of existing infrastructure, including reservoirs, water treatment facilities, and pumping stations, among others. While water resource system capacity expansion planning has been extensively addressed in the literature, focusing on optimizing the sizing, timing, and sequencing of projects [101, 184, 234], few of these publications directly tackle freshwater supply shortages due to SLR. Instead, decisions are often made in anticipation of future temperature rises, precipitation changes, and drought events

Each accommodation strategy discussed comes with its advantages and limitations concerning the practical operation and control of saltwater intrusion [73, 103, 153, 163, 237]. To overcome the limitations of individual techniques, many publications addressing aquifer management problems consider mixed strategies, such as combining freshwater injection and saline water extraction [183] or integrating subsurface barriers and recharge wells [143]. The general overview of the extant research on adaptation of water supply infrastructure is presented in Table 5.

4.3 Wastewater and Urban Drainage Infrastructure

Urban drainage systems are among the most critical flood control systems, that, if properly operated and designed, will enhance the overall coastal system's resilience and hence, its ability to respond and adapt to future flooding events. Different wastewater and urban drainage systems, including the centralized and the decentralized on-site systems, have different vulnerabilities to future risks propagated by SLR. Therefore, while planning adaptation strategies, different solutions can be addressed for protecting, accommodating, or retreating (where applicable) in the context of these systems. One of the widely addressed adaptation strategies for urban drainage and wastewater networks is partially or completely rehabilitating the existing network or optimizing the operations of the network components – pumping operations in particular- in order to minimize total flood-related damage while minimizing maintenance and operational costs. In this section, we classify articles according to operational decisions and network-rehabilitation strategies.

Table 5: Overview of research papers addressing adaptation of water supply infrastructure

			Protection	Accommodation						Methodology				
Ref.	Year	Country of Case Study	Sub-surface barrier walls and dams	Capacity Expansion	Groundwater abstraction	Saltwater desalination	Water diversion/Reservoir Management	Managed Aquifer Recharge (MAR)	Saltwater abstraction	Experimental	Analytical	Process Simulation	Agent-based Simulation	Optimization
[203]	2001	India							✓			✓		
[148]	2003	Greece						✓						✓
[165]	2004	-						✓						✓
[116]	2007	Greece			✓									✓
[101]	2008	Taiwan		✓								✓		✓
[149]	2008	Greece			✓									✓
[222]	2008	Belgium						✓				✓		
[113]	2009	Oman							✓			✓		
[142]	2009	Japan	✓							✓				
[68]	2009	India						✓						✓
[63]	2009	India			✓							✓		
[23]	2010	Iran						✓						✓
[173]	2010	-							✓			✓		
[88]	2010	-		✓			✓							✓
[143]	2011	Japan	✓					✓		✓				
[4]	2011	UK				✓		✓				✓		✓
[209]	2011	Australia			✓							✓		✓
[184]	2012	Jordon		✓										✓
[74]	2012	UK					✓							✓
[138]	2013	-						✓	✓		✓			
[153]	2013	UK		✓										✓
[163]	2013	UK		✓										✓
[84]	2013	UK					✓						✓	✓
[104]	2015	UK			✓							✓		✓
[115]	2015	Greece			✓							✓		✓
[137]	2017	-			✓			✓			✓			
[177]	2017	Iran			✓								✓	✓
[114]	2018	Thailand					✓							✓
[80]	2017	-					✓							✓
[73]	2018	UK		✓										✓
[19]	2019	-	✓					✓		✓		✓		
[52]	2019	-	✓							✓		✓		
[17]	2020	-	✓									✓		
[18]	2020	-						✓				✓		
[154]	2020	-						✓		✓		✓		

[182]	2020	USA	✓	✓		✓	✓				✓
[223]	2020	USA			✓			✓	✓	✓	

Protection - Most protection strategies rely on network rehabilitation of the wastewater and urban drainage networks and their components. These practices encompass increasing pump and/or pipeline capacities, adding detention facilities, and relocating any network components. Critical decisions must be made, such as choosing between pipe replacements and rehabilitation options [159], determining optimal locations and capacities for stormwater detention facilities, pump capacities, and defining start-up and stop levels for each pump [105]. Additionally, decisions regarding the optimal locations and capacities of storage facilities, which act as buffers during peak flooding events, need careful consideration [62, 230]. The timing and implementation plan can also be vital and may be addressed through a staged adaptation decision-making approach [238]. Objectives addressed in these decisions include minimizing costs, covering flood-related damage costs, investment costs, and rehabilitation costs [105, 230, 238].

Accommodation - Designing efficient operational management methodologies is a common approach for accommodating this infrastructure. In this context, pump stations play a crucial role as the primary flood control facilities in an urban drainage system. They regulate the incoming flow throughout the entire drainage network during flooding events. Generally, when the sea level surpasses the urban drainage system level, the pumping station's control gate is closed to prevent seawater from entering the system. In this scenario, stormwater can only be drained through pumping. Therefore, optimizing pump operations when the drainage gate is closed becomes crucial for effective flood control. Key decisions in this context involve adjusting pumping rates [102, 239], determining sewage system storage capacity [55] to minimize overall flood levels [102], managing overflow volume [242], and minimizing operational costs by optimizing the number of pump switches [242].

Some drainage networks have detention facilities that are constructed to temporarily store the storm water during peak periods and slowly drain it afterwards. Improperly draining this delayed flow may coincide with the upstream floods and aggravate the flood risk downstream. Therefore, deciding on the optimal operational requirements of these storage facilities is essential in minimizing the risks of flooding [160]. According to Borsanyi et al. [46], while many of the developed models are based on static loading design, it is necessary to consider dynamic loading conditions in order to adapt the system to new operational policies under uncertain climate events. In a more recent study, Jafari et al. [107] employ a simulation-optimization methodology to derive real-time control policies for operating the pumping stations of the urban drainage systems. The authors highlight several other articles that deploy real-time dynamic control modelling in the context of urban drainage and water supply networks.

While urban drainage and wastewater networks are actively adapting to future risks, there is a notable lack of attention given to the vulnerability of septic systems, particularly concerning surface and inland flooding resulting from SLR. Septic systems are highly susceptible to catastrophic failures as groundwater levels rise. To mitigate potential impacts, both research and practical applications propose two main strategies: replacing existing septic systems with innovative alternatives or extending sewer systems to replace septic systems entirely [10]. Accommodating septic systems involves exploring innovative solutions, such as the use of shallow narrow leach fields. These new systems receive effluent that has undergone secondary treatment in an advanced treatment component, allowing the infiltrative surface to be positioned higher in the soil profile compared to conventional leach fields. Moreover, the shallow narrow designs incorporate frequent time-dosing of wastewater to prevent prolonged periods of soil saturation. An early application of this advanced system took place in Rhode Island, New England, USA [60, 156]. The general overview of the extant research on adaptation of water supply infrastructure is presented in Table 6.

4.4 Power Generation and Transmission Infrastructure

In response to anticipated risks due to future climate conditions, energy systems can be adapted either by protecting critical infrastructure components to minimize their exposure and enhance their ability to resist extreme events or by accommodating the network architecture and its operations to absorb impacts while causing no or minimal disruptions. In this section, we present some of the measures discussed in the literature for accommodating energy infrastructure. We limit our focus to the strategies that can be applied in attenuating the effects of sea level rise. For a more general discussion on addressing the effects of climate policy on electric power infrastructure from a decision-modeling perspective we refer the interested reader to the review article by Parker at al. [166].

Table 6: Overview of research papers addressing adaptation of Waste Water and Urban Drainage Infrastructure

			Accommodation						Methodology		
			Accommodation Strategy		Network Components Considered						
Ref.	Year	Country of Case Study	Operational Adjustments	Structural Rehabilitation	Pumps	Pipes	Control Gates	Storage Facilities	Simulation	Optimization	Analytical
[239]	1999	-	✓		✓					✓	
[55]	2011	Taiwan	✓		✓				✓		
[13]	2012	Spain						✓			✓
[102]	2013	Taiwan	✓		✓					✓	
[133]	2013	China	✓		✓					✓	
[180]	2013	Portugal		✓				✓	✓		
[244]	2014	Korea		✓	✓	✓			✓	✓	
[235]	2014	Taiwan	✓		✓				✓	✓	
[243]	2015	Korea	✓		✓						✓
[242]	2016	Korea	✓		✓		✓	✓		✓	
[62]	2016	Portugal		✓				✓	✓	✓	
[160]	2016	Korea	✓	✓				✓	✓	✓	
[105]	2017	Columbia		✓	✓	✓		✓		✓	
[230]	2017	China		✓				✓		✓	✓

[246]	2017	Singapore		✓		✓			✓	✓	
[108]	2018	Iran	✓				✓		✓	✓	
[107]	2018	Korea	✓		✓		✓			✓	
[231]	2018	China		✓		✓				✓	
[238]	2018	China		✓	✓			✓		✓	
[241]	2019	Iran	✓					✓	✓	✓	
[159]	2019	Columbia		✓		✓		✓		✓	
[248]	2019	China								✓	
[195]	2020	USA	✓		✓		✓		✓		
[98]	2022	Iran		✓		✓				✓	
[10]	2023	USA		✓	✓					✓	✓

Protection – Strengthening the critical network components helps protect them against the possible impacts of climatic risks. Such protection measures include reinforcing poles in the distribution networks and protecting switching stations and substations. Protecting power stations and generators can be done either by installing a variety of devices, such as insulators, relays, and circuit breakers, that are designed to isolate equipment and contain any disturbances [169, 208], or by elevating or relocating them to unexposed or elevated areas. As an example of the latter case, the Texas Medical Center relocated all critical infrastructure components to areas above the projected flood elevation in the aftermath of the severe inland flooding associated with the Allison tropical storm in 2001 [75].

Another protection strategy consists of transitioning from overhead feeder lines to underground ones. Failure of over-headlines post severe weather events accounts for the majority of the massive blackouts. Consequently, using buried power lines can increase physical security, and reduce transmission losses, and maintenance requirements [201]. In addition, the construction of new transmission lines and generators developed to accommodate new and smart technologies will help reinforce the system in the long term [170]. These approaches are considered by Con Edison as part of their USD 1 billion investment to enhance New York City's resilience against future risks due to SLR [225].

Accommodation – As energy systems evolve to accommodate supply, generation, and transmission infrastructure, there is a discernible shift from conventional, centralized, and less resilient models to more sustainable and decentralized community-level systems [200]. These future systems not only embrace decentralization but also strive to enhance supply diversity by integrating fluctuating renewable energy sources like wind, geothermal, and solar power with residual resources such as waste and biomass [141]. Diversification of energy supply and infrastructure is one of the most important schemes to enhance the resilience of the energy system. A flexible energy system featuring a combination of both centralized and distributed generation facilities can enhance system diversity and ensure the continued flow of energy [201]. In this regard, the distributed energy resources (DERs) are changing the manner of transmission of energy through the utility power grid [32], enabling diversification of energy supply and transmission through an integrated network of Distributed Generation (DG), storage and microgrids [136]. Although DER is poised to be an attractive solution for communities that are highly susceptible to risks due to climate change, and in particular SLR, integrating the DER architectures with the existing power systems will affect the economics and performance of power delivery. Consequently, proper planning and technical design is an area of interest for research and practice [157].

In addition to diversification of supply and responsiveness of loads, a resilient energy system needs the redundant, spare capacity to buffer against sudden power outages due to disruptive events without impacting the system through power circulation [201]. Energy storage is one technology that helps maintain the system's reliability by rapidly responding to changes in load, supply load during transmission or distribution interruptions, and correct load voltage profiles. There are many advances in storage power solutions including, but not limited to, batteries, flywheels, ultra-capacitors, hybrid battery-ultra capacitors, and superconducting energy storage systems [45, 188]. One important point is that storage capacity should be coupled with connectivity infrastructure to facilitate the transmission of the stored energy to nodes affected by a disruptive event.

In addition to transitioning the planning and design of energy infrastructure, implementing effective operational strategies is crucial for efficient operations and maintenance. A key operational strategy is blackout prevention planning, aimed at maintaining an uninterrupted power supply or minimizing the duration of blackout restoration. This involves deploying special protection schemes, known as System Integrity Protection Schemes (SIPS), to minimize the probability of grid failure and prevent the propagation of damage. Automatic under-frequency load shedding is one such scheme that balances load and generation, restoring the system frequency to normal operation. Another effective strategy is under-voltage load shedding, which mitigates damage by shedding load at the lowest voltage point when disruptions cause voltage drops in a specific area. For a detailed analysis of blackout prevention planning strategies, readers are referred to [170], where the authors provide comprehensive insights into different strategies and their implementation, drawing from experiences in Thailand.

While numerous adaptation options exist in the energy sector, most reviewed articles primarily focus on enhancing resilience to generic disruptions or hurricane events. There is a notable gap in addressing adaptation modeling for SLR risks. A significant amount of research is needed to better understand the costs, effectiveness, and potential for adaptation, especially considering the timescales associated with impacts, particularly those related to rising sea levels [56]. Bridging this gap will be essential for developing strategies that can effectively address the unique challenges posed by SLR in the energy sector. Some of the considered articles are summarized in Table 7.

4.5 Farming and Agriculture

In this section, we provide a summary of adaptation strategies outlined in the literature to safeguard and accommodate agricultural production in the face of future risks stemming from SLR. Beyond the exploration of hard and soft protection measures aimed at minimizing the exposure of agricultural lands, as well as other infrastructure and critical assets, numerous crop and soil management practices have been introduced in the literature. This section will provide a summary of these practices, encompassing techniques such as crop rotation, the adoption of new crops and varieties, strategic sowing, inter-cropping, and the implementation of soil conservation techniques, along with effective fertilizer management strategies.

Table 7: Overview of research papers addressing adaptation of Power Infrastructure to different disruptions

					Accommodation			Methodology		
Ref.	Year	Country of Case Study	Risk	Protection	Decentralization	Diversification	Redundancy	Optimization	Simulation	Analytical
[57]	2017	UK	Temperature			✓			✓	✓
[89]	2019	China	General			✓		✓		
[132]	2021		General			✓	✓	✓		
[8]	2022		General			✓		✓		
[208]	2022	USA	Flooding	✓				✓	✓	
[186]	2023		General			✓		✓	✓	
[240]	2023	China/Ghana	General		✓	✓	✓	✓	✓	

Protection - To maintain low groundwater levels effectively, an impactful strategy involves constructing dikes equipped with sluices (Wei systems) to manage drainage and irrigation, complemented by electric pumping [54]. Simultaneously, consolidating small systems into larger ones, alongside the use of dikes, serves to prevent floodwater from encroaching onto agricultural lands during high tides. By efficiently draining the land during low tides, this approach helps sustain low groundwater levels, thereby safeguarding agricultural lands from potential flooding, soil salinity, and other consequential impacts that could adversely affect crop yields.

In addition, construction of embankments with enhanced drainage facilities can be a feasible protection measure in some deltas as they allow the passage of fresh, non-saline water at appropriate times of the year to raise polder lands with sediments. An example is the Case of Bangladesh's Coastal Embankment System and the running improvement project (CIEP), which is designed to support the rehabilitation of the whole embankment system with an existing 6,000 km of embankments and 139 polders [7]. The project is expected to protect the coastal areas and improve agricultural yield by reducing saline water intrusion in selected polders. As of May 2019, the project has protected 21,700 ha of gross area and upgraded 130.58 km of embankment.

When considering ecosystem-based (soft) protection measures in areas with slight to moderate salinity, the cultivation of Boro rice and sweet water shrimp farms proves effective in reclaiming soil salinity. This integrated approach is exemplified in the Khulna-Bagherat region of Bangladesh, where both crops and aquaculture (fish, shrimp, etc.) coexist on the same land. This mixed land use facilitates the rapid leaching of soluble salts, effectively reducing water salinity within a short period [97]. Additionally, coastal afforestation, which involves the cultivation of both mangrove and non-mangrove plantations, is highly beneficial for protecting coastal lands from erosion. This practice serves multiple purposes, including the conservation of biodiversity and the creation of a natural barrier against winds and storms, as observed in Sri Lanka [85] and Bangladesh [106].

Accommodation – There is a growing emphasis on adapting agricultural practices to mitigate the adverse impacts of climate change on various crops' growth [187] and enhance overall operational efficiency in farming [90]. Practices documented in the existing literature can be broadly categorized into three main groups: (1) crop management, (2) soil management, and (3) water management. Crop management practices can be customized to adapt agricultural production to challenges like increased salinity and rising groundwater tables or to mitigate the effects of waterlogging. Some of these strategies involve cultivating salt-tolerant crops and forage species [214]. For instance, in Egypt, crops such as wheat, onion, maize, tomato, and pepper have been successfully grown using saline water or a blend of saline and fresh water. Similarly, in the United States, saline water is effectively employed for irrigation in the Southwest region to cultivate crops like cotton, sugar beets, and small grains [197].

Beyond the introduction of salt-tolerant crops, cultivating crops resilient to higher groundwater tables proves to be an effective strategy in addressing the challenges posed by rising groundwater beyond a specific threshold. Wheat, a major grain crop, is particularly susceptible to variations in the groundwater table. Developing new varieties of wheat holds the potential to reduce dependence on electric pumping and mitigate crop damage caused by elevated water tables. Another approach to alleviate the impacts of rising groundwater levels and waterlogging is through Strategic Deep Tillage (SDT). This method has been proposed to enhance drainage in the subsoil, thereby minimizing the likelihood of waterlogging occurrences [145].

Other crop management practices include managing seedbeds and grading fields to minimize local accumulation of salts [197]. In addition, crop rotation by the inclusion of biological-fixing nitrogen crops is a widespread practice across the UK [187]. This practice involves planting different crops sequentially on the same plot of land to improve soil health and optimize nutrients in the soil and therefore, helps to adapt the soil to the increased salinity. For example, in the agricultural zones of Montana in the USA, farmers use several crop management strategies to adapt their fields to climate variabilities. They cultivate a portion of small grains in a crop-fallow rotation, aiming to let the fallow period accumulate soil moisture for subsequent crops. Some farmers adopt a practice of leaving a field fallow every other year, while others opt for a continuous cropping strategy [15].

Appropriate soil management practices can improve soil quality and crop productivity through increased infiltration, reduced surface runoff, and improved availability of water and nutrients [145]. Soil management practices include tillage, ploughing, sanding, using chemical amendments, mineral fertilizers, organic manures, and mulching. Salinity management is one of the soil management practices that is concerned with the safe use of salt-affected soils and saline water for crop and forage production [197]. Among these practices are the occasional leaching of salt from crop roots and blending saline water with fresh water. Salinity control by leaching is based on applying more water than that needed by the crop during the growing season. The excess water helps leach the salts by moving them below the root zone by deep percolation [37]. Also, one of the strategies proposed to combat the indirect effects of salinity on soil fertility is adequate nitrogen management. Planning a successful nitrogen management program is an important challenge faced by researchers in agronomy [249] where the timing and methodology of the application of nitrogen into the soil are very critical. For instance, early application holds the risk of losing it through leaching without the crop taking it, and late application might not pay off after tasseling, and the plant will not take up the nitrogen introduced. Therefore, proper timing, rates, and allocation are critical decisions to be made constrained by external climatic factors such as rainfall intensity.

Another important soil management practice suggests the use of raised bed system to improve the soil structure and increase yield productivity under waterlogged conditions. These 10-30 cm raised beds allow water to drain away from the root zones, alleviating the effects of logged waters [174]. Salinity is projected to indirectly impact yield and agricultural productivity due to its role in causing nutrient deficiency. Therefore, adequate nitrogen management is a compelling challenge faced by researchers in agronomy [249].

Water management strategies encompass the implementation of an efficient water distribution system [64, 152] and meticulous irrigation scheduling. This includes demand-based irrigation scheduling, the installation of advanced irrigation systems, and the adoption of various irrigation techniques aimed at boosting yields, enhancing crop quality, and optimizing water usage [125]. Previous research has proposed several avenues to enhance irrigation efficiency [34]. These include agronomic improvements, such as introducing higher-yield crop varieties and implementing improved crop husbandry. Technical advancements, such as laser leveling of flood irrigation to improve irrigation uniformity, are also recommended. The adoption of more efficient irrigation practices like drip irrigation, which reduces soil evaporation and drainage, is highlighted.

In regions where irrigation water is saline, desalination emerges as an attractive method for increasing crop yields. However, it's important to note that this approach may pose challenges if essential nutrients are removed during desalination and not reintroduced into the soil [37]. Beyond desalination, runoff farming is widely employed in arid and semi-arid areas. In this technique, water harvesting methods, such as floodwater spreading, are crucial due to the absence of a regular freshwater supply. Surface runoff occurs when rainfall intensity exceeds infiltration and other catchment abstractions, leading to floods. Flood spreading is employed as a method to manage the risks and hazards associated with floods, groundwater recharge, and crop production [16].

Efficient surface drainage is a critical strategy in enhancing the resilience of agricultural systems since it reduces the likelihood of flooding of agricultural lands and helps control salinity. Other forms of drainage include subsurface drainage (such as mole drains), horizontal drainage (such as tile drainage), and vertical subsurface drainage that help lower groundwater table, and ensure a suitable root environment by combating water logging as well as controlling salinity in the root zone by leaching out the concentrated salt solutions [145]. In addition, bio-drainage is another eco-friendly and promising option for the reclamation and management of waterlogged saline soils. Bio-drainage involves pumping of excess soil water using bio-energy through deep-rooted vegetation with a high rate of transpiration [178].

Table 8 provides an overview of the reviewed papers on adaptation of agricultural infrastructure. We refer the readers to [145, 175, 190, 197, 224] for more in-depth reviews.

5 Research Gaps and Future Directions

This paper provides a detailed review and analyzes diverse adaptation strategies employed by infrastructure systems in response to sea-level rise (SLR) and their integration into decision-making frameworks. Our examination highlights a growing interest in utilizing decision-making frameworks to enhance infrastructure resilience. However, significant gaps exist, presenting substantial opportunities for the Operations Management community to contribute to and bridge these research gaps through interdisciplinary collaborations [49, 61]. In a recent paper, Atasu et al. [24] provides a comprehensive review of research on sustainability using the perspective of manufacturing and service operations. In general, while the extant literature provides valuable insights regarding decision making on infrastructure resilience, thus far, the majority of the solutions are narrow in scope, focusing on a particular risk or discipline-specific problem. Planning and implementation of comprehensive solutions to enhance system-wide resilience of any infrastructure necessitates systems perspective and holistic approaches with a high degree of integration and coordination.

Consequently, convergence research that goes beyond transdisciplinary collaborations and incorporate stakeholder perspectives has been increasingly encouraged as an urgent need by scholars, practitioners, and both gonvernmental agencies [14]. This trend focuses on deep integration among complex non-academic and academic groups to address grand challenges embedded in regional systems [212]. We contend that OM community has much to offer for these efforts with its paradigms and unique capacity to synthesize multiple perspectives into comprehensive, integrated, and coordinated solutions that enhance infrastructure and community resilience against the impacts of SLR. In that regard, OM research serves as an invaluable catalyst for addressing this pressing challenge.

Table 8: Overview of research papers addressing adaptation of agriculture infrastructure

					Accommodation			Methodology		
Ref.	Year	Country of Case Study	SLR-Risk	Protection Strategy	Crop Management	Soil Management	Water Management	Simulation	Optimization	Analytical/ Empirical
[34]	1999	UK	Salinity		✓		✓			✓
[54]	1999	China	Waterlogging	✓						✓
[50]	2003	Central Asia	-		✓		✓			✓
[28]	2007	Australia	Waterlogging			✓				✓
[178]	2008	India	Salinity + Waterlogging				✓			✓
[37]	2009	Israel	Salinity				✓	✓		✓
[33]	2009	Italy	Waterlogging		✓			✓		
[130]	2013	Switzerland	Salinity + Waterlogging			✓	✓		✓	
[64]	2013	India	-				✓		✓	
[204]	2014	South Asia	Salinity + Waterlogging		✓	✓	✓		✓	

Integration in this context extends beyond the mere combination of multiple components of systems and adaptation schemes; it also involves the coordination of various stakeholders, decision-makers, and considerations of jurisdictional and geographic boundaries [36]. The failure to establish coordinated adaptation protocols has been described as an implementation dilemma, where nationwide policies are often developed without considering the perspectives of local governments or private stakeholders, who may have different motivations or constraints. These situations can result in conflicts, as demonstrated in the case of the Charleston Slough in San Francisco Bay, USA, where multiple entities with overlapping jurisdictions led to the duplication of efforts and the loss of resources and efficiency [171]. Therefore, the necessity of incorporating integrated and coordinated decision-making in climate adaptation is widely acknowledged in the literature. Kelly et al. [117] highlight the following areas where integration can be incorporated into climate decision-making: (1) integrated impact assessment, (2) integrated treatment of issues (or integrated adaptation), and (3) stakeholder integration. In what follows, we elaborate on the research gaps and potential directions in these areas.

5.1 Integrated Assessment of Impacts: Systems View and Multidimensionality

A critical prerequisite for making system-wide (globally) effective decisions is to incorporate multiple dimensions of risks and resilience into quantifiable measures. There are four main sources of risks in the context of SLR: coastal flooding, coastal erosion, salt-water intrusion, and rising groundwater levels. In order to conduct an effective impact assessment that encompasses multiple risks, it is necessary to combine different process models [56, 117]such as flood models with coastal erosion models [206]. In addition to the integrated assessment of risks, because urban infrastructures are densely collocated, it is logical that there should be some impacts propagating from one infrastructure to other connected infrastructures [42]. Therefore, the direct and cascading impacts within and between infrastructure systems must be evaluated. For example, when assessing the vulnerability of transportation infrastructure to SLR, the impacts the overflowing sewer pipes have on transportation infrastructure in case of flooding events must be addressed.

In the related literature, multiple researchers develop tools and strategies to quantify cascading impacts of disruptions in infrastructure components [100, 121, 215]. Such integration is interdisciplinary, and therefore its success is highly dependent on interdisciplinary research efforts. Despite these efforts, only a few studies use the outcomes in systematic adaptation decision-making models. Additionally, the majority of the proposed integrated impact assessment methods are limited to addressing physical interdependencies between infrastructures – in which the output of one node is an input to another. Besides the physical interdependence there are other forms of infrastructure inter-dependencies identified by [190], namely, cyber interdependence, geographic interdependence, and logical interdependence. To the best of our knowledge, barely any study addresses these different forms of inter-dependencies, at least in the context of SLR adaptation decision-making.

In enhancing resilience, assessed risks and vulnerabilities must be mapped into quantifiable, multidimensional metrics and measures. Quantifying resilience allows for comparing adaptation options, assessing costs and benefits, and informing investment decisions. Such measures can be utilized in objective functions and constraints in building comprehensive decision-making models. Recent studies propose resilience functions constructed based on *leading indicators* [12, 167] and demonstrate incorporation of composite resilience metrics into optimization framework [10, 11].

5.2 Integrated Adaptation Strategies: From Local Solutions to Global Perspective

Critical infrastructure systems are densely collocated and interdependent, relying on each other for effective functioning. This interdependence underscores the crucial need for a holistic and integrated approach to the management and maintenance of critical infrastructure systems. Any disruption or failure in one system can trigger cascading effects on others, emphasizing the significance of an integrated approach in sustaining resilient and adaptive urban infrastructure systems. Both the direct and indirect impacts of SLR across systems must be incorporated into decision-making frameworks. The compelling challenge remains to be transitioning from a line defense strategy to territory defense in composing decision models in the context of SLR adaptation.

In our review, as summarized in Section 4, we observe that while integrated adaptation within individual infrastructure systems has received widespread attention, there is a notable gap in addressing integration across infrastructure systems and between sectors in the context of SLR adaptation decision-making. Integration is crucial across infrastructure systems, where changes made in one sector might have impacts on other social, economic, or environmental sectors [117]. For instance, building a flood defense structure in a location might have implications for natural habitat diversity in that area. Another aspect of integration relates to incorporating multiple adaptation strategies and their interrelations in the context of enhancing resilience across multiple regions. For example, combining protective measures such as building a seawall in a location and devising retreat strategies in an adjacent area may yield the most efficient and economically sound scenario. As such, large-scale decision models tailored for joint optimization in this context have considerable potential to contribute to producing actionable system-wide solutions.

5.3 Stakeholder integration: Coordination and Inclusion

Climate adaptation holds significance and attracts interest from a diverse range of stakeholders. Active engagement and participation of these stakeholders not only provide support but also offer valuable guidance throughout the planning and implementation stages. Therefore, it becomes crucial to identify key stakeholders early in the adaptation planning process, understanding their interests, responsibilities, and positions. This early recognition enables the development of appropriate variables, objectives, and constraints in decision-making models.

From a policy-making perspective, integrating multiple objectives and stakeholder incentives into the decision-making process is imperative to ensure actionable solutions. For instance, some stakeholders, driven by a risk-averse approach, advocate for substantial investments in infrastructure to minimize expected damages [72]. Conversely, decision-makers representing fiscally conservative stakeholders may argue for cost-effective solutions. A traditional single-objective function may mask these trade-offs, leading to locally optimal solutions inconsistent with stakeholders' preferences [79]. Achieving a globally optimal adaptation policy that addresses conflicting stakeholder visions is a challenging research problem that merits further exploration. OM research can significantly contribute to linking disparate perspectives across disciplinary and institutional boundaries, and provide solutions on global scale for coastal systems across short- and long-term horizons with both vertical and horizontal coordination. While the former aims to coordinate communities, NGO's, scientists and decision makers in a region, the latter focuses on effectively linking stakeholders across regions. The two-way coordination in this context is meant to shift from local solutions (line defense) to system-wide optimization (territory defense).

Apart from the lack of integration and coordination in adaptation decision-making, there's a dearth of comparative studies analyzing the resulting adaptation plans derived from various decision-making approaches. Understanding the variances between methodologies, such as robust, adaptive, and Info-Gap approaches, all considering future uncertainties, is crucial for devising flexible and dynamic adaptation plans. Comparative studies by Hall et al. [95] and Matrosov et al. [153] report reasonably similar yet not identical adaptation outcomes from Robust-Decision Making and Info-Gap Models. Conversely, Roach et al. [191] identify substantial disparities among adaptation strategies from these methodologies, suggesting the potential for a mixed methodology. Similarly, Gersonius et al. [81] observe notable distinctions when comparing Real Options Analysis and the Adaptation Tipping Points Approach. These conflicting findings indicate the need for further investigation and caution in drawing definitive conclusions regarding the discrepancies between these approaches. As this research field is still in its nascent stages, a thorough understanding and well-established insights are yet to be attained.

6 Conclusion

The primary objective of this paper is to curate and synthesize a diverse array of adaptation practices across multiple infrastructure sectors. This compilation aims to establish a robust foundation for the fields of Operations Management (OM), acting as a conduit to seamlessly integrate valuable knowledge into decision-making models. While the tools within the realms of OM undeniably address the climate and community-centric challenges outlined in this paper, a shift in perspective is warranted. As Wassenhove emphasizes [221], it is imperative to adjust our approach and confront these formidable issues through collaborative endeavors, combining methodologies and tools from various fields. This undertaking requires a steadfast commitment to investigating pertinent, urgent concerns and substantiating their potential impact. In this regard, we envision this paper as a key driver for transferring essential insights regarding the feasibility and limitations of various climate adaptation strategies and how they can be integrated into a decision-making framework to inform the adaptation of critical infrastructure systems to sea-level rise risks.

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