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OPTIMAL TRANSPORTATION AND SHORELINE INFRASTRUCTURE INVESTMENT PLANNING UNDER A STOCHASTIC CLIMATE FUTURE

Final Report

by

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EXECUTIVE SUMMARY

This paper studies the problem of optimal long-term transportation investment planning to protect from and mitigate impacts of climate change on roadway performance. The problem of choosing the extent, specific system components, and timing of these investments over a long time horizon (e.g., 40-60 years) is modeled as a multi-stage, stochastic, bi-level, mixed-integer program wherein cost-effective investment decisions are taken in the upper level. The effects of possible episodic precipitation events on experienced travel delays are estimated from solution of a lower-level, traffic equilibrium problem. The episodic events and longer-term sea level changes exist on different time scales, making their integration a crucial element in model development. The optimal investment strategy is obtained at a Stackelberg equilibrium that is reached upon solution to the bilevel program. A recursive noisy genetic algorithm (rNGA), designed to address large-scale applications, is proposed for this purpose. The rNGA seeks the optimal combination of investment decisions to take now given only probabilistic information on the predicted SLR trend for a long planning horizon and associated likely extreme climatic events (in terms of their frequencies and intensities) that might arise over that planning period. The proposed solution method enables the evaluation of decisions concerning where, when and to what level to make infrastructure investments. The proposed rNGA has broad applicability to more general multi-stage, stochastic, bilevel, nonconvex, mixed integer programs that arise in many applications. The proposed solution methodology is demonstrated on an example representing a portion of the Washington, D.C. Greater Metropolitan area adjacent to the Potomac River. The total expected cost incurred over the transportation network over a 60-year study time horizon was quantified. This application of the proposed methodologies on the case study suggests a positive return on investment for preparedness.

1.0 INTRODUCTION

Increased storm frequency and intensity, increased total precipitation, sea level rise (SLR) and tides as high as 20 feet or more are among the concerns associated with climate change. More frequent temporary or permanent inundation of transportation elements are expected as a consequence. This paper proposes optimization-based solution techniques for long-term transportation investment planning in protection and mitigation strategies that aim to safeguard performance of our roadway networks.

SLR is perhaps the best documented and most accepted impact of climate change. SLR projections, however, require analysis of complex processes, including glacial melting and thermal expansion of the oceans. Thus, these predictions are at best uncertain. SLR projections for year 2100 range, for example, from several centimeters to more than a meter (Powell, 2009). Thus, they are typically given in terms of trajectories (e.g. best, worst and average cases) as depicted in Figure 1**Error! Reference source not found.**, where best and worst-case estimates have low occurrence probabilities. They can also be described in terms of probability distributions. Similar uncertainty exists in storm-event occurrence and resulting storm surges.

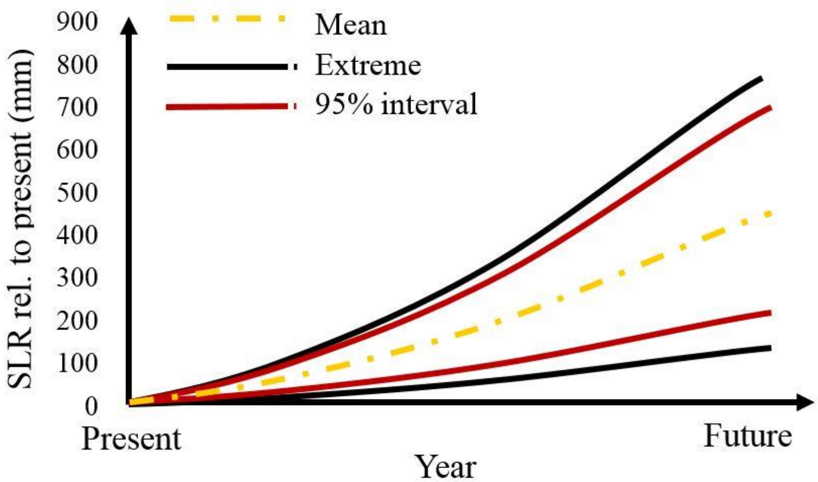

Figure 1: Schematic range of SLR projections

Increases in the frequency and extent of coastal flooding events due to storm surges in recent years are noted by Reuters (2014). They point out that for five coastal cities along the East Coast of the U.S. since 2001 there has been an average of 20-25 days at which water levels exceeded flood thresholds. Comparatively, before 1971, an average of only 5 days at such water levels occurred in the same cities. This increase arose with an estimated SLR during that 30-year period of approximately 0.1 meters (NOAA, 2016). Predictions of future SLR range from as little as one foot to as high as 6.6 feet in the next 85 years (Walsh et al., 2014).

Flooding events can affect components of the transportation network from all modes. Examples include: roadway links, transit stations, subway tunnels, airports, ports and rail lines. Loss of components will impact the network topology and connectivity and therefore system-level performance (i.e. throughput, travel time, fuel consumption, pollution). These events can lead to very significant monetary losses, whether due to direct losses (e.g. loss of use of a roadway link) or indirect effects (e.g. requiring a mode change from rail to road). Consider only the five coastal cities of Baltimore, Boston, New York, Philadelphia and Providence. A SLR of 0.66m by 2050, if correctly projected (Powell, 2009), would potentially impact $7.4 trillion worth (unadjusted for inflation) of civil infrastructure assets in these cities. On a global scale, it is estimated that $28 trillion (unadjusted) in world-wide assets associated with 136 “port megacities” would be at risk given a SLR of 0.5m by 2050 (Powell, 2009).

Flood predictions on the order of several feet for four of the five Boroughs of New York City during severe storms are projected under predicted SLR rates 0.24 to 1.08 meters(Jacob et al., 2007). Several works predict traffic disruptions and weakened infrastructure as a result of increased storm intensity and higher sea levels (Peterson et al., 2008; Savonis et al., 2008). The impact of even less extraordinary weather events on ground-based transportation systems will be intensified under higher sea levels (Council, 2010). In fact, approximately 60,000 miles of coastal roads in the United States are already exposed to flooding from coastal storms and high waves (TRB, 2008). Exposure of road infrastructure in coastal areas to SLR and storm surges shortens the life expectancy of highways and roads, requiring more frequent maintenance, repairs, and rebuilding. More than two billion people live within 60 miles of a coastline (Powell, 2009). Moreover, roadways in such coastal areas serve as critical evacuation routes that must be protected from flooding and damage for use in emergencies (TRB, 2008).

Actions or interventions can be taken to prevent or mitigate the effects of SLR and related increases in storm surges on the civil infrastructure. Actions may also be required in a flood event to reduce water levels and restore services. In support of response (or recovery) actions, preparatory acts, such as acquiring and prepositioning of resources, may be required. In determining which preparatory actions to take, trade-offs between mitigation efforts requiring significant capital investment and coping with post-event damage must be considered. Mitigation efforts hedge against effects that would be possible under future predictions of SLR levels and storm frequency increases that may not be realized; however, if realized their impacts can be tremendous and response capabilities may be limited or costly. In fact, the impacts may include permanent inundation and destruction of assets. In many cases, one can justify the costs of mitigation through savings due to their effectiveness in increasing network resilience to SLR and storm surge and recognizing that the costs incurred as a consequence of inaction would surpass the costs of implementing mitigation options (Lu et al., 2012).

Although the effectiveness of investments in combating the impacts of SLR and storm surge have been quantified (Lu et al., 2012), a virtually unlimited budget would be required to implement all mitigative actions that would be needed to prevent damage in a worst-case or other more extreme scenarios. Given budgetary limitations, the number of actions that can be implemented at a given point in time is restricted in practice and, therefore, optimal investment decisions over a time horizon are required. Such decisions require an ability to quantify the impact of combinations of investments in the infrastructure along with monetary costs due to post-event system-level performance losses. Furthermore, they must be taken under uncertainty in event and impact prediction, which makes the planning process for combatting climate-change impacts an even more complicated task.

This paper proposes mathematical modeling and solution techniques for determining optimal transportation infrastructure investment decisions over a time horizon. Specifically, a bi-level, multi-stage, nonlinear, integer stochastic program is developed. Its objective is to minimize long-term costs of maintaining a functioning transportation roadway network prone to probabilistic SLR levels and coastal flooding events. Costs capture increased travel delays for drivers as well as monetary expenses needed to reinforce components, construct protective elements, and rebuild after destruction. Decisions produced by the model provide the optimal combination of such actions, the network elements to which they should be applied and time period in which they should be implemented. This tool can aid decision makers in choosing between projects and justifying costly protective actions. Before proceeding to a description of the mathematical model (section 3), a review of related literature is given (Section 2). A recursive noisy genetic algorithm (rNGA) that can be applied to larger, realistic problem instances is proposed for solution of the model (Section 4). The rNGA seeks the optimal combination of investment decisions to take now given only probabilistic information on the predicted SLR trend for a long planning horizon (on the order of 40-60 years) and associated likely extreme climatic (episodic) events that might arise over that planning period. Decisions taken now will be optimal knowing that appropriate cost-effective actions can be taken in future time periods within the planning horizon as the SLR trend is revealed over time, climatic events are realized and future event probabilities are revealed. That is, no commitment to future investment is required for future periods, but that optimal investments at these later points in time will be made is assumed. The rNGA can be applied to other bilevel, nonlinear, integer, multi-stage stochastic programs. These mathematical tools are illustrated on a case study involving a portion of the Washington, D.C. Metropolitan Area roadway network in the vicinity of the Potomac River (Section 5).

2.0 BACKGROUND

Many journal articles, conference papers, reports, news articles, television programs, and other forms of media discuss the potential of SLR to impact the civil infrastructure, including the transportation network and its components (Titus et al. 2009; Berry et al., 2012; Karl et al., 2009; Douglass and Krolak, 2008; Gallivan et al., 2009; Reuters, 2014). Possible impacts are described in (Koetse and Rietveld, 2009; Bloetscher et al., 2012; Chang et al., 2010). These impacts may be from direct consequences of SLR, e.g. gradual inundation, or storm surges whose sizes are influenced by SLR. They also list possible actions to be taken to combat such impacts. Table 1 provides a synthesis of the various impacts of SLR on different elements of the transportation network.

Some researchers have developed coastal flood maps for particular SLR and storm frequency estimates. These maps are used to assess potential future costs of damage, identify likely affected geographic areas, and evaluate community vulnerability (Lu and Peng, 2011; Wu et al., 2013), as well as other impacts. Analyses made under only one predicted state, that is ignoring the uncertainty in these predictions, may result in misleading findings. A few other works in the literature quantify the level of impact on the transportation system or other coastal infrastructures in terms of travel time increase (Lu and Peng 2011; Lu et al., 2012; Suarez et al., 2005), pollution (Lu et al., 2012), and other system performance metrics (Suarez et al., 2005; Eijgenraam et al., 2014) for specific locations given uncertainty in SLR forecasts in the impact analysis. These along with two other related qualitative works are summarized in Table 3; they are described in more detail next.

Table 2 lists mitigative and adaptive actions identified in the literature to combat these impacts. Green infrastructure should also be added to this list. Some works discuss the existence of trade-offs between inaction and costs for taking preventative actions (Lu et al., 2012). Finally, vulnerability assessments aimed at identifying at-risk transportation infrastructure components are also presented (Bloetscher et al., 2012; TRB, 2008; Savonis et al., 2008).

Table 1: Impacts of SLR on Transportation Network (synthesized from: Savonis et al., 2008; Karl et al., 2009; Bloetscher et al., 2012; Koetse and Rietveld, 2009; TRB, 2008)

Sector	**Impacts**
Land	Inundation of roads and rail lines in coastal areas More frequent or severe flooding of underground tunnels and low-lying infrastructure Erosion of road base and bridge supports
Marine	Harbor and port facilities prone to higher tides and storm surges Reduced clearance under bridges Impacts on the navigability of channels
Air	Potential for closure or restrictions for operations Inundation of airport runways in coastal areas

Some researchers have developed coastal flood maps for particular SLR and storm frequency estimates. These maps are used to assess potential future costs of damage, identify likely affected geographic areas, and evaluate community vulnerability (Lu and Peng, 2011; Wu et al., 2013), as well as other impacts. Analyses made under only one predicted state, that is ignoring the uncertainty in these predictions, may result in misleading findings. A few other works in the literature quantify the level of impact on the transportation system or other coastal infrastructures in terms of travel time increase (Lu and Peng 2011; Lu et al., 2012; Suarez et al., 2005), pollution (Lu et al., 2012), and other system performance metrics (Suarez et al., 2005; Eijgenraam et al., 2014) for specific locations given uncertainty in SLR forecasts in the impact analysis. These along with two other related qualitative works are summarized in Table 3; they are described in more detail next.

Table 2: Mitigative and Recovery Actions (synthesized from: Savonis et al., 2008; Karl et al., 2009; Bloetscher et al., 2012; Koetse and Rietveld, 2009; TRB, 2008)

Sector	Actions
Land	Elevating streets and rails Improving drainage systems of coastal roads Protecting bridges, tunnels and transit entrances Increasing pumping capacity of tunnels Relocating roads and rail lines inland Protecting high value coastal real estate with levees, seawalls and dikes
Marine	Increasing the frequency of bridge openings Raising dock and wharf levels and retrofitting other facilities to provide adequate clearance Protecting terminal and warehouse entrances Elevating bridges and other structures Raising or construction of new jetties and seawalls to protect harbors
Air	Elevating runways Constructing or raising protective dikes and levees Relocating some runways

Table 3: Summary of most relevant works in the literature

Title	**Economic Analysis of Impacts of SLR and Adaptation Strategies in Transportation**	**A Probabilistic Methodology to Estimate Future Coastal Flood Risk Due to Sea Level Rise**	**Impacts of Flooding and Climate Change on Urban Transportation: A System-wide Performance Assessment of the Boston Metro Area**	**Vulnerability Analysis of Transportation Network under Scenarios of Sea Level Rise**	**Scenario-based Climate Change Risk Analysis for Transportation Infrastructure using GIS**	**Economically Efficient Standards to Protect the Netherlands Against Flooding**
Year	2012	2008	2005	2011	2014	2014
Authors	Lu et al.	Purvis et al.	Suarez et al.	Lu and Peng	Wu et al.	Eijgenraam et al.
Mitigative Options	✓	✗	✗	✗	✗	✓
Probabilistic Projections	✗	✓	✗	✓	✓	✓
Storm Surge	✗	✓	✓	✗	✓	✓
Direct Costs	✓	✓	✗	✗	✗	✗
Indirect Costs	✓	✗	✓	✓	✗	✗
Normative	✗	✗	✗	✗	✗	✓
Multi Objective	✗	✗	✗	✗	✗	✗

Purvis et al. (2008) presented a methodology to account for the uncertainty in SLR predictions in risk assessment of land prone to coastal flooding. They use a Monte Carlo simulation procedure that samples from a triangular probability distribution function on the range of SLR projections for each point in time. Storm surge patterns are predicted using a two-dimensional model of coastal inundation given predicted SLR values. By combining flood risk maps with land-use value maps, risk of loss due to coastal flooding is estimated. They concluded that undertaking a risk assessment using the most plausible SLR value may significantly underestimate monetary losses, because it fails to account for the impact of low-probability, high-consequence events. A scenario-based risk assessment approach is also presented in (Wu et al., 2013) and (Lu and Peng, 2011). Both works focus specifically on the transportation infrastructure. Wu et al. used a geographic information system (GIS) to create risk maps for three climate change-risk scenarios (with low, medium and high risk) to show the potential impact on transportation assets in a particular location. They combined these maps to create a single GIS-based risk map. Lu et al. assessed the reduction in accessibility by traffic analysis zone (TAZ) due to inundation under probabilistic SLR scenarios also within a GIS framework and for a particular location.

In addition to considering the vulnerability of civil infrastructure to SLR, a couple of these works investigate performance loss in transportation networks due to SLR impacts. Suarez et al. (2005) assessed the impact of changes in land use and demographics due to changes in climatic conditions and resulting river and coastal flooding events on the performance of an urban transportation network. Results are aggregated over a 100-year time horizon. Their results show a doubling in delays and lost trips. Lu et al., (2012) proposed a framework to conduct cost-benefit analysis related to the implementation of preventative actions for a transportation network predisposed to SLR. They considered two projected values of SLR for year 2100 and three possible sets of preventative actions for a particular transportation system: (1) complete shoreline protection, (2) partial shoreline protection, and (3) transportation infrastructure protection. By taking into account both direct inundation and indirect travel time costs, they concluded that protective actions along with managed retreat otherwise is the best long-run, adaptation strategy for combatting the impacts of SLR.

For a network at risk, there are numerous mitigative and adaptive actions and combinations of these actions that can be considered for preventing or combating SLR effects. Thus, the determination of an optimal investment strategy can be difficult. Moreover, such decisions must be made given uncertainty in SLR and storm surge predictions. Considering the extraordinary costs of such actions and the high costs of damage and increased network delays due to inaction, having a normative model to aid in choosing the actions to be implemented on the various system components at various points in time over a planning horizon is necessary. It appears Eijgenraam et al., (2014) are the first to present such a normative model for optimal investment decisions related to flood protection infrastructure. Using cost-benefit analysis and mixed-integer nonlinear programming techniques, they demonstrated the efficiency of imposing dike height requirements for flood protection. Their approach builds on work of Van Dantzig (1956) who proposed a cost-benefit analysis (CBA) for determining the optimal dike height in which investment requirements are balanced against societal benefits from avoiding flood damage.

This paper extends the capabilities of prior works in several important directions. Specifically, it provides a tool that: (1) can support optimal investment decision-making, (2) considers tradeoffs between different mitigation option types, (3) explicitly accounts for probabilistic projections for SLR and storm properties (frequency, intensity), (4) addresses multi-temporal issues allowing for staged decisions over a long time horizon, and (5) models both direct and indirect costs on the transportation system and its users.

3.0 MATHEMATICAL MODEL

3.1 MODEL OVERVIEW

The problem of determining the optimal investment decisions for minimizing the impact of the effects of climate change on the transportation roadway network under a set of possible SLR-storm event scenarios is formulated as a bi-level, multi-stage, integer stochastic program. In the long-run, the tool provides the optimal investment strategies and recourse actions to minimize expected cost given predicted storm frequencies and probabilistic SLR projections. Notation used in the mathematical program are introduced next, followed by related concepts and formulation details.

3.2 NOTATION

Sets

A	set of links, a, in the roadway network
N	set of network nodes, n, representing roadway intersections and points of demand
W	set of origin-destination (OD) pairs, w
K_w	set of paths k between OD pair $w \in W$
M	set of midpoints in time, which can be taken as problem stages
Ω^m	set of possible sea level rise projections at midpoint $m \in M$,
F^m	set of flooding events over all projections in Ω^m for midpoint $m \in M$
E	$= \{wall, raise, drain\}$, set of investment decision types

Random variables and their realizations

ω^m	at midpoint $m \in M$, random sea level rise event (i.e. projection) $\omega^m \in \Omega^m$ may realize
ξ^m	$= (\mathbf{L}^m, \mathbf{R}^m, \mathbf{\Pi}^m, \mathbf{\Theta}^m)$, the vector of random sea level, water level, flood event damage and flood event frequency variables, respectively, for midpoint $m \in M$

$\xi^m(\omega^m)$ $= \left(\mathrm{L}^m(\omega^m), \mathrm{R}^m(\omega^m), \Pi^m(\omega^m), \Theta^m(\omega^m)\right)$ given realization ω^m for midpoint $m \in M$

$\mathrm{L}^m(\omega^m)$ $= [l_a^m(\omega^m)]_{\forall a \in A}$, the vector of sea level values along the links under realization ω^m at midpoint $m \in M$,

$\mathrm{R}^m(\omega^m)$ $= \left[r_{f,a}^m(\omega^m)\right]_{\forall f \in F^m, a \in A}$, the matrix of link water levels for all flooding events $f \in F^m$ under realization ω^m at midpoint $m \in M$,

$\Pi^m(\omega^m)$ $= \left[\pi_{f,a}^m(\omega^m)\right]_{\forall f \in F^m, a \in A}$, where $\pi_{f,a}^m(\omega^m)$ is the link damage extent given between zero (no damage) and one (signifying complete destruction) associated with all flooding events $f \in F^m$ under realization ω^m at midpoint $m \in M$,

$\Theta^m(\omega^m)$ $= \left[\theta_f^m(\omega^m)\right]_{\forall f \in F^m}$, the vector of flooding event frequencies under realization ω^m at midpoint $m \in M$,

$\mathrm{C}_0^m(\omega^m)$ $= \left[c_{0,a}^m(\omega^m)\right]_{\forall a \in A}$, vector of post-event link capacities for realization of random vector $\boldsymbol{\xi}^{\boldsymbol{m}}$, $\xi^m(\omega^m)$, at midpoint $m \in M$

$\mathrm{T}_0^m(\omega^m)$ $= \left[t_{0,a}^m(\omega^m)\right]_{\forall a \in A}$, vector of post-event link travel times for realization of random vector $\boldsymbol{\xi}^{\boldsymbol{m}}$, $\xi^m(\omega^m)$, at midpoint $m \in M$

$\mathrm{C}_f^m(\omega^m)$ $= \left[c_{f,a}^m(\omega^m)\right]_{\forall a \in A}$, vector of post-event link capacities under flooding event $f \in F^m$ for realization of random vector $\boldsymbol{\xi}^{\boldsymbol{m}}$, $\xi^m(\omega^m)$, at midpoint $m \in M$

$\mathrm{T}_f^m(\omega^m)$ $= \left[t_{f,a}^m(\omega^m)\right]_{a \in A}$, vector of post-event link travel times under flooding event $f \in F^m$ for realization of random vector $\boldsymbol{\xi}^{\boldsymbol{m}}$, $\xi^m(\omega^m)$, at midpoint $m \in M$

Parameters

D $= [d_w]_{\forall\, w \in W}$, vector of known OD travel demand

$\mathrm{C^o}$ $= [c_a^o]_{\forall a \in A}$, known vector of pre-event link capacities

$\mathrm{T^o}$ $= [t_a^o]_{\forall a \in A}$, known vector of pre-event link free flow travel times,

H $= [h_a]_{\forall a \in A}$, vector of link heights above a datum, h_a is set according to the height of the lowest section of link a to capture the link's susceptibility to inundation

Γ_{max} $= \left[\gamma_{max}^{wall}, \gamma_{max}^{raise}, \gamma_{max}^{drain}\right]$, vector of reasonable maximum values for cumulative infrastructure improvement, where $\Gamma_{max}^{wall} = \left[\gamma_{max,a}^{wall}\right]_{\forall a \in A}$ is the vector of maximum total height of sea wall protection, $\Gamma_{max}^{raise} = \left[\gamma_{max,a}^{raise}\right]_{\forall a \in A}$ is the vector of maximum total height by which each link can be raised and $\Gamma_m^{drain} = \left[\gamma_{m,a}^{drain}\right]_{\forall a \in A}$ is the vector of maximum achievable improvement in drainage capacity for link drainage systems

Δ $= \left[\delta_{a,k,w}\right]_{\forall a \in A, k \in K_w, w \in W}$, link-path incidence matrix, where $\delta_{a,k,w} = 1$ if path

	$k \in K_w$ uses link a and = 0 otherwise
$\bar{b}_{m,a}^{wall}$	cost of building one unit height of sea wall for link a at stage m, depends on the length of the wall
$\bar{b}_{m,a}^{raise}$	cost of raising link a for one unit of height for link a at stage m, depends on the length and number of lanes of the link
$\bar{b}_{m,a}^{drain}$	cost of one unit improvement in drainage for link a at stage m, depends on the length of the link
$\bar{b}_{m,a}^{rebuild}$	cost of rebuilding link a in stage m, depends on the length and number of lanes in the link
$\bar{b}_{f,a}^{response}(\omega^m)$	cost of taking a response action for link a at stage m under flooding event $f \in F^m$ for realization of random vector $\boldsymbol{\xi}^m$, $\xi^m(\omega^m)$, at midpoint $m \in M$
α	used in total travel time calculations, a multiplier that adds weight to temporary effects of precipitation events; it also includes monetary conversion based on passenger value of time
β	used in in total travel time calculations, a multiplier that aggregates passenger travel times for the time period; it also includes monetary conversion based on passenger value of time
I	$= [i^m]_{\forall m \in M}$, vector of multipliers that adjust monetary costs at each stage for inflation to allow comparisons of their net present values

Upper level decision variables

Γ_m	$= [\Gamma_m^{wall}, \Gamma_m^{raise}, \Gamma_m^{drain}, \Gamma_m^{rebuild}]$, vector of m^{th}stage decision variables, where $\Gamma_m^{wall} = [\gamma_{m,a}^{wall}]_{\forall a \in A}$ is the vector of continuous-valued additional height of sea wall protection, $\Gamma_m^{raise} = [\gamma_{m,a}^{raise}]_{\forall a \in A}$ is the vector of continuous-valued heights by which each link is raised, $\Gamma_m^{drain} = [\gamma_{m,a}^{drain}]_{\forall a \in A}$ is the vector of continuous-valued level of improvement of the drainage system along the links, and $\Gamma_m^{rebuild} = [\gamma_{m,a}^{\text{rebuild}}]_{\forall a \in A}$, where $\gamma_{m,a}^{rebuild} = 1$ if link a is rebuilt during period $m \in M$ as needed to respond to significant damage due to flooding events prior to this time period
$\Gamma_{m,f}^{response}$	$= [\gamma_{m,f,a}^{\text{response}}]_{\forall a \in A}$, vector of link recovery actions under flooding event $f \in F^m$ for realization of random vector $\boldsymbol{\xi}^m$, $\xi^m(\omega^m)$, at midpoint $m \in M$, where $\gamma_{m,f,a}^{\text{response}} = 1$ if a recovery action is taken for link a to address damage due to flooding event $f \in F^m$ for realization $\xi^m(\omega^m)$ and 0 otherwise

Lower level decision variables

$X_0^m(\omega^m)$ $= \left[x_{0,a}^m(\omega^m)\right]_{\forall a \in A}$, vector of post-event link flows for realization of random vector $\boldsymbol{\xi^m}$, $\xi^m(\omega^m)$, at midpoint $m \in M$

$X_f^m(\omega^m)$ $= \left[x_{f,a}^m(\omega^m)\right]_{\forall a \in A}$, vector of post-event link flows under flooding event $f \in F^m$ for realization of random vector $\boldsymbol{\xi^m}$, $\xi^m(\omega^m)$, at midpoint $m \in M$

$P_0^m(\omega^m)$ $= \left[p_{0,k,w}^m(\omega^m)\right]_{\forall k \in K_w, w \in W}$, vector of post-event path flows for realization of random vector $\boldsymbol{\xi^m}$, $\xi^m(\omega^m)$, at midpoint $m \in M$

$P_f^m(\omega^m)$ $= \left[p_{f,k,w}^m(\omega^m)\right]_{\forall k \in K_w, w \in W}$, vector of post-event path flows under flooding event $f \in F^m$ for realization of random vector $\boldsymbol{\xi^m}$, $\xi^m(\omega^m)$, at midpoint $m \in M$

Functions used in the objectives

Let vector $S^m = \{(\Gamma_0, \omega^1), (\Gamma_1, \omega^2) \dots, (\Gamma_{m-1}, \omega^m)\}$ store the history of investment decisions and realized SLR values from time period prior to and including *m*. Then:

$$invst^m(S^m) = \sum_e \sum_a \bar{b}_{m,a}^e \gamma_{m,a}^e + \sum_a \bar{b}_{m,a}^{rebuild} \gamma_{m,a}^{rebuild},$$

m^{th}-stage investment and rebuilding costs given damage due to cumulative impact of flooding events in prior stages

$$tt(S^m) = \alpha \sum_{f \in F^m} \sum_a \theta_f^m(\omega^m) x_{f,a}^m(\omega^m)\, t_{f,a}^m(\omega^m) + \beta \sum_a x_{0,a}^m(\omega^m)\, t_{0,a}^m(\omega^m),$$

aggregated cost of travel times incurred by all network users in stage m based on link states under realization $\xi^m(\omega^m)$, previous investments and historical events in S^m due to episodic events (first term) while accounting for the frequency of related flooding events and permanent inundation from SLR (second term); converted to monetary values through parameters α and β

$$resp^m(S^m) = \sum_{f \in F^m} \sum_a \theta_f^m(\omega^m) \bar{b}_{f,a}^{response}(\omega^m) \gamma_{m,f,a}^{response}$$

aggregated costs of actions taken in stage m for responding to inundation as might arise from, for example, a breach of a seawall; events treated independently

$$t(v, c_{f,a}^m(\omega^m)) = t_a^0 + m_a \left[\frac{v}{c_{f,a}^m(\omega^m)}\right]^{n_a},$$

Bureau of Public Roads (BPR) function for given flow v and a capacity $c_{f,a}^m(\omega^m)$

3.3 SOURCES OF STOCHASTICITY AND THE TIME HORIZON

Stochasticity in the model arises from uncertainty in climate-change forecasts and a range of SLR and storm frequency predictions. These sources of uncertainty are considered in scenario generation for the study horizon. This horizon, perhaps on the order of 60 years, is broken down into several periods of uniform duration on the order of 10 to 20 years. The state of the system in each period is represented by its state at its mid-point. Figure 2 shows the SLR prediction ranges and time periods with chosen representative points. For a given prediction of SLR at such a point in time, the frequency of episodic events of different magnitude can be predicted stochastically. The episodic events and longer-term sea level changes exist on different time scales, making their integration a crucial element in model development.

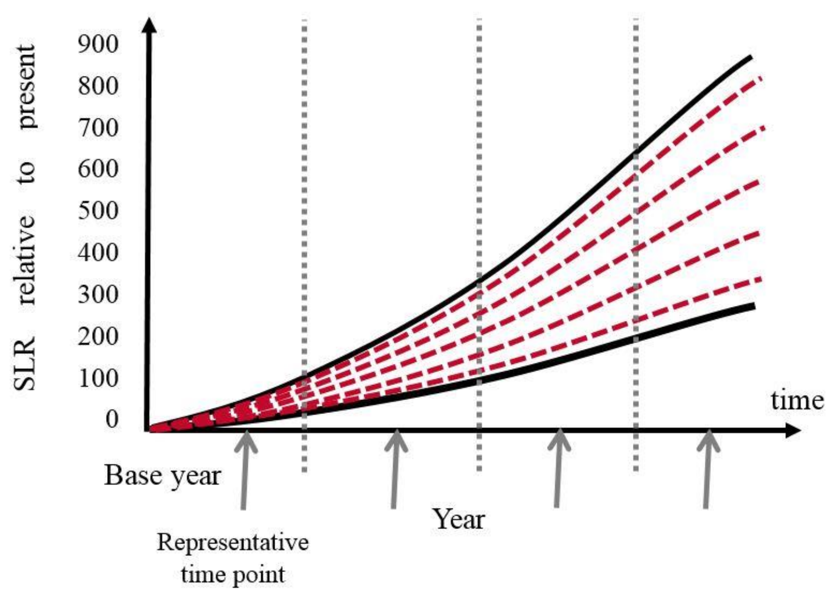

Figure 2: SLR trajectory predictions

Each time period within the planning horizon is represented by its midpoint; it is associated with a stage in the stochastic program. The impact of investment decisions taken within a time period is presumed to take effect at the end of that time period.

Figure 3 shows periods with associated mid-points.

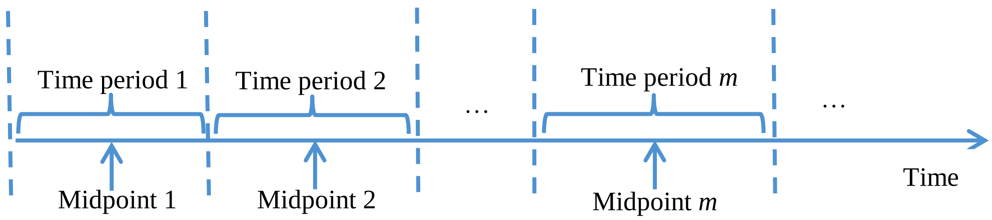

Figure 3: Time elements of the problem

Sea level and storm frequency are elements of the vector $\boldsymbol{\xi}^m$. Each is a random variable. Their predicted probability distributions are dependent on their realizations from the previous period, $\xi^{m-1}(\omega^{m-1})$. Moreover, for any midpoint m, each realization of sea level, ω^m, produces a specific storm frequency distribution, their correlation created through the underlying climate change processes. This dependency is captured during scenario generation. A single realization of random variables $\boldsymbol{\xi}^m$, $\xi^m(\omega^m)$, at time point m produces a number of system states, defined in terms of the functioning links (i.e. damaged or temporarily flooded), one for each realized storm event f. An additional storm-free state is included, representing the functionality of the system under realized levels of water, $\mathrm{L}^m(\omega^m)$, due only to sea level rise. Travel time is aggregated over the study time horizon and accounts for changes in travel time from all events arising in this period, whether temporary or permanent.

3.4 FORMULATION

The problem is formulated as a bi-level program. At the upper level, the government agency charged with making public investment decisions (the leader) determines an optimal investment strategy. Without loss of generality, investments specified in this formulation include: building sea walls, improving drainage, and raising elements. They might also include the implementation of green infrastructure, for example. These investments determine the coping capacity of the links to resist rising levels of water, and thus, determines link functionality under each system state. At the lower level, under each SLR-storm event scenario, and given infrastructure improvements from the upper level, system users (the followers) choose their routes assuming a user equilibrium will be reached. The optimal investment strategy is obtained when a Stackelberg equilibrium is reached between the upper level investment decisions and choices made by system users in response.

Figure 4 shows this leader-follower structure, elements of which will be defined in the following subsections.

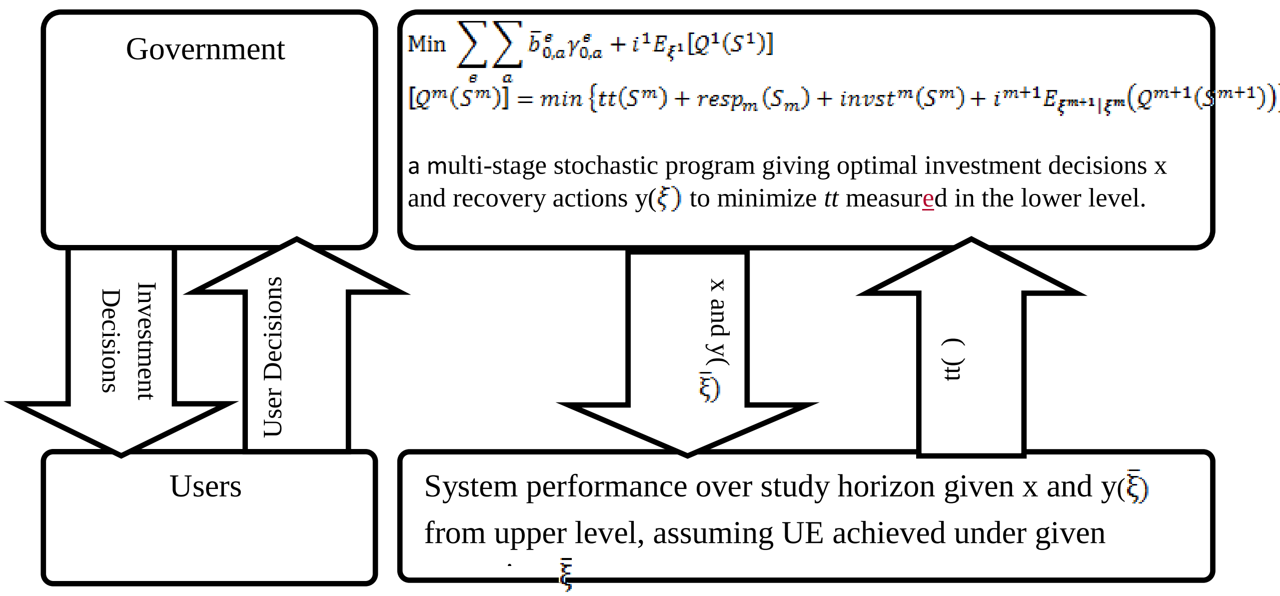

Figure 4: Bi-level Structure of the Developed Model

The model enables the evaluation of decisions concerning where, when and to what level to make infrastructure investments. If investments are made to mitigate the occurrence of flooding and other SLR-related damage, then in a storm event the number of available (undamaged) options will be larger, overall system capacity will be greater, and the performance of the system will generally be improved. If, however, such mitigative actions are not taken in advance, traffic links will be down, time for recovery will be needed and reconstruction may be required. In the former case, the burden of the cost is bared even if SLR estimates turn out to be erroneously high, and savings are incurred only if forecasted flooding events are prevented. In the latter case, damage is incurred and costs of repair are inevitable. Additionally, post-event actions can have both short and long-term benefits. Short-term benefits are derived from the immediate alleviation of inundation or damage, thereby affecting current system performance. For certain types of damage, if no repair action is taken, there are long-term consequences in terms of loss of performance. The effects of investments are also carried forward in time.

3.4.1 Upper-Level of Bi-Level Formulation

Optimality of the upper level problem is guided by an objective function given by Equation (1). The objective captures the costs of current preventative decisions made at time 0 as well as the expected costs of later investments and increased traffic delays for a probabilistic future. Current preventative decisions are made at time 0. Based on the realization of future events and actions taken in preceding time periods, additional preventative decisions are made in later stages. These actions are determined at the end of each period and benefit the network in coming periods. Recovery decisions can be taken as recourse in every realization during each period (post event) for each SLR-storm event scenario. Optimality of infrastructure improvement decisions is determined, thus, at a given point in time for a range of potential future SLR-storm scenarios. At time zero, the objective function rolls together the monetary and travel costs incurred from investments made over the time horizon and costs of travel delay due to intermittent flooding events over the same horizon. Thus, the objective (1) is recursive. It captures the tradeoffs between costs of increased delay to drivers as a result of road closures and monetary expenses due to pre- and post-event actions. That is, it captures the benefits of preventative, protective actions on reducing the likelihood of particular damage states for affected links, as well as future impacts of component reconstruction after incurring significant damage.

$$\text{Min} \sum_{e} \sum_{a} \bar{b}_{0,a}^{e} \gamma_{0,a}^{e} + i^{1} E_{\xi^1}[Q^1(S^1)] \tag{1}$$

Subject to

$$\gamma_{0,a}^{e} \leq \gamma_{max,a}^{e}, \qquad e \in E, \ a \in A \tag{2}$$

$$\gamma_{0,a}^{e} \geq 0, \qquad e \in E, \ a \in A \tag{3}$$

$$\left[Q^{|M|}\left(S^{|M|}\right)\right] = 0, \tag{4}$$

where the cardinality of M, $|M|$, gives the number of stages.

$$[Q^m(S^m)] = min\left\{tt(S^m) + resp_m(S^m) + invst^m(S^m) + i^{m+1} E_{\xi^{m+1}|\xi^m}\left(Q^{m+1}(S^{m+1})\right)\right\} \tag{5}$$

$Q^m(S^m)$ defined in Equation (5) is the value function of the m^{th}-stage recourse problem with $m \geq 1$. This value function includes costs incurred during the m^{th} period under realization $\xi^m(\omega^m)$ as part of history S^m plus the expected cost during later time periods under a set of probabilistic SLR-storm scenarios. Constraints 2 and 3 limit investment decisions for stage zero to be between reasonable limits. Constraint 4 provides the boundary condition for the recursive formulation through which costs and benefits stop accumulating upon completion of the time horizon.

Later stages are subject to Constraints 6 through 14:

$$c_{f,a}^{m}(\omega^{m}) \leq max\left\{h_a + \sum_{e}\sum_{\dot{m}=0}^{m-1}\left(\gamma_{\dot{m},a}^{e}\right) + \gamma_{m,f,a}^{\text{response}} - r_{f,a}^{m}(\omega^{m}), 0\right\} Mc_{a}^{o}, \qquad a \in A,\ \ f \in F^{m} \tag{6}$$

$$c_{f,a}^{m}(\omega^{m}) \leq \ Mc_{a}^{o}\sum_{j=1}^{m-1} max\left\{\gamma_{j,a}^{rebuild} - \sum_{k=j}^{m-1}\sum_{f\in F^{k}} \theta_{f}^{k}(\omega^{k})\pi_{f,a}^{k}(\omega^{k}), 0\right\}, a \in A, f = 0 or \in F^{m} \tag{7}$$

$$c_{0,a}^{m}(\omega^{m}) \leq \ max\left\{\left(\left(h_a + \sum_{\dot{m}=0}^{m-1}\left(\gamma_{\dot{m},a}^{wall} + \gamma_{\dot{m},a}^{raise}\right) - l_{a}^{m}(\omega^{m})\right), 0\right\} Mc_{a}^{o}, \qquad a \in A \tag{8}$$

$$c_{f,a}^{m}(\omega^{m}) \leq \ c_{a}^{o}, \qquad a \in A,\ \ f \in F^{m} or\ f = 0 \tag{9}$$

$$t_{f,a}^{m}(\omega^{m}) = t_{a}^{0} + m_a\left[\frac{x_{f,a}^{m}(\omega^{m})}{c_{f,a}^{m}(\omega^{m})}\right]^{n_a}, \qquad a \in A,\ \ f \in F^{m} or\ f = 0 \tag{10}$$

$$\sum_{m'=0}^{m} \gamma_{m',a}^{e} \leq \gamma_{max,a}^{e}, \qquad e \in E,\ \ a \in A \tag{11}$$

$$\gamma_{m,a}^{rebuild} \geq 0, \qquad a \in A \tag{12}$$

$$\gamma_{m,a}^{e} \geq 0, \qquad e \in E,\ \ a \in A \tag{13}$$

$$\gamma_{m,f,a}^{\text{response}} \geq 0, \qquad a \in A,\ \ f \in F^{m} \tag{14}$$

Constraints 6 through 8 capture the reduction in link capacity to zero when a link is permanently (Constraints 6) or temporarily (Constraints 8) inundated due to SLR or episodic flooding events, respectively. When the original height of the link, h_a, additional protection provided through mitigative actions taken in prior stages and response actions taken post-event together cannot prevent inundation of a link a, Constraints 6 **Error! Reference source not found.**model its failure. For a time period, Constraints 8 model the reduction in link capacity due to SLR. Specifically, the constraints preclude the application of response actions and drainage improvements designed to mitigate precipitation episodes. These actions cannot restore capacity or protect from SLR. Constraints 7 further capture the cumulative impact of episodic flooding events on the long-term functionality of the links and counter effects of rebuilding actions taken in earlier stages. A link is considered as impassible when damage due to flooding events since the infrastructure element was last in pristine condition accumulates and its value exceeds one or becomes impassible due to temporary inundation. Constraints 9 enforce link capacity limits. A link is presumed to have either full or zero capacity (i.e. it is either up or down), the latter occurring when the link is physically damaged or inundated. M, a large number, can be removed from the constraints to permit the modeling of intermediate capacity levels.

To calculate link travel times the well-known BPR function is adopted in Equations (10). These equations rely on post-response link flows, $x_{f,a}^{m}(\omega^{m})$, computed from solution of the lower level UE and link capacities, $c_{f,a}^{m}(\omega^{m})$, enforced in constraints 6-8, free flow link travel times, t_a^0, and BPR function parameters, m_a and n_a (herein, $m_a = 0.15$ and $n_a = 4$ for all $a \in A$).

Maximum levels of protection accumulated through all taken investments are enforced through Constraints 11. Constraints 12 through 14 guarantee non-negativity requirement for all m^{th}-stage investments, rebuilding and response decisions.

3.4.2 Lower level of the Bi-level Formulation

The lower level problem determines the link flows and travel times needed to calculate the total travel time $tt(\omega^{m})$ in the objective function of the upper-level problem. The lower-level problem seeks a UE under objective function 15 given network link states in terms of their capacities $C_f^{m}(\omega^{m})$ under flooding event f and realization ω^{m}. When $f = 0$, capacities $C_0^{m}(\omega^{m})$ are taken under the prevailing network conditions during that period.

$$min \sum_{a} \int_0^{x_{f,a}^{m}(\omega^{m})} \left(t_a^0 + m_a \left[\frac{v}{c_{f,a}^{m}(\omega^{m})} \right]^{n_a} \right) dv, \qquad (15)$$

$$\sum_{k} p_{f,k,w}^{m}(\omega^{m}) = d_{w}, \qquad w \in W \tag{16}$$

$$x_{f,a}^{m}(\omega^{m}) = \sum_{w}\sum_{k} \delta_{a,k,w} p_{f,k,w}^{m}(\omega^{m}), \qquad a \in A \tag{17}$$

$$p_{f,k,w}^{m}(\omega^{m}) \geq 0, \ k \in K_{w}, \ w \in W \tag{18}$$

$$x_{f,a}^{m}(\omega^{m}) \geq 0, \ \ a \in A \tag{19}$$

Equations (16) ensure that demand for every OD pair is met within the traffic assignment. Equations (17) determine link flows from path flows. Equations (18) and (19) are lower-level non-negativity constraints.

4.0 THE RECURSIVE NOISY GENETIC ALGORITHM

Exact solution of this bilevel, nonlinear, integer, recursive and multi-stage stochastic program is formidable even for toy problem instances. One option available for this UE formulation is to replace the lower level by equivalent Karush Kuhn Tucker (KKT) conditions (Larsson and Patriksson, 1997) and apply the disjunctive-constraints method to linearize required complementary slackness. This creates an equivalent single-level program (Kuhn and Tucker, 1951), but requires additional binary variables, and thus additional nonconvexities, to the formulation. Hence, a globally optimal solution will be difficult to obtain for real-world problem instances. One can apply linearization techniques to approximate nonlinear terms, creating a mixed-integer, linear program. Several techniques exist to address such problems (of direct relevance see: Wang and Lo, 2010); although, solution of the resulting mixed-integer program would be obtainable only for small problem instances. An alternative, heuristic approach that can be applied to larger, realistic problem instances is proposed herein. Specifically, a recursive Noisy Genetic Algorithm (rNGA) is presented.

4.1 STRUCTURE OF THE RNGA

As in typical genetic algorithms, the rNGA requires chromosome design, initial population creation, crossover and mutation strategies, fitness evaluation and settings for continuation to the next generation, termination and elitism. The conceptualization of this climate impact investment problem in the prior section as a recursive program needed to capture the branching structure of this multi-stage decision problem significantly complicates its design, however. This section describes the design with emphasis on this branching structure.

4.2 CHROMOSOME DESIGN

Each chromosome represents a solution in which each major investment decision (additional height of seawall, additional element height, improved drainage or rebuilding) for each link in the network is set at every stage. Each constituent investment setting is stored in a single gene. The genes take 0-1 values where drainage and rebuilding decisions are taken. Integer values, between zero and an upper bound, represent a seawall height increment or height by which an element is raised.

Figure 5 illustrates that portion (a string) of a chromosome associated with stage 1. Link investment decisions are indicated. Strings associated with each stage are stored separately with identity information maintained in an extra row. This information includes the stage number, as well as the strings' numbers from prior stages to which this string has been appended.

A chromosome is created from strings of genes, each string of which is associated with a stage. When multiple strings are appended together, they form a base string. A number of strings associated with stage 3 can be appended to a block of already appended strings (base strings) from stages 0 through 2, for example, to form new building blocks (base strings - representing decisions taken in stages 0 through 3) or longer base strings for additional chromosomes that span the entire time horizon (beyond stage 3).

Rebuild {0,1}	Seawall {0,1,..,6}	Raising {0,1,..,5}	Drainage {0,1}	
0	2	0	1	Link 1
0	0	0	0	Link 2
. . .	. . .	. . .	. . .	. . .
1	0	3	0	Link n

String number	Stage number	Base string of stage 0
148	1	8

Figure 5: Representation of One String of a Chromosome

4.3 BRANCHING (RECURSIVE) STRUCTURE OF THE RNGA

It is typical in GAs to evaluate each chromosome independently based on a procedure for fitness computation. In NGAs, this procedure is applied over a set of randomly chosen realizations of random variables to compute the expected value of the "noisy" fitness function. In this multi-stage setting, this fitness value computation is more complicated. The goal is not to evaluate the fitness of a whole chromosome, but rather of a 0^{th}-stage set of decisions (the first string) given many possibilities of how future decisions would be taken in future stages under these first-stage decisions. Creation and evaluation of future-stage decisions involves construction of a string in the chromosome for each later stage. These later stage decisions are effectively recourse actions or postponed investments. Their feasibility and effectiveness depends on the history: $S^m = \{(\Gamma_0, \omega^1), (\Gamma_1, \omega^2) \dots, (\Gamma_{m-1}, \omega^m)\}$. The probability of a future SLR trend along with precipitation events depends on realizations in prior stages. Evaluation, thus, requires the creation of a host of stage-related decisions all tying back to decisions taken in the first stage. It is conducted on probable realizations for the future whose occurrence likelihood depends on the history. Thus, fitness computation requires both assessments that rolls forward to the end of the time horizon and backward for evaluation.

This process is depicted in

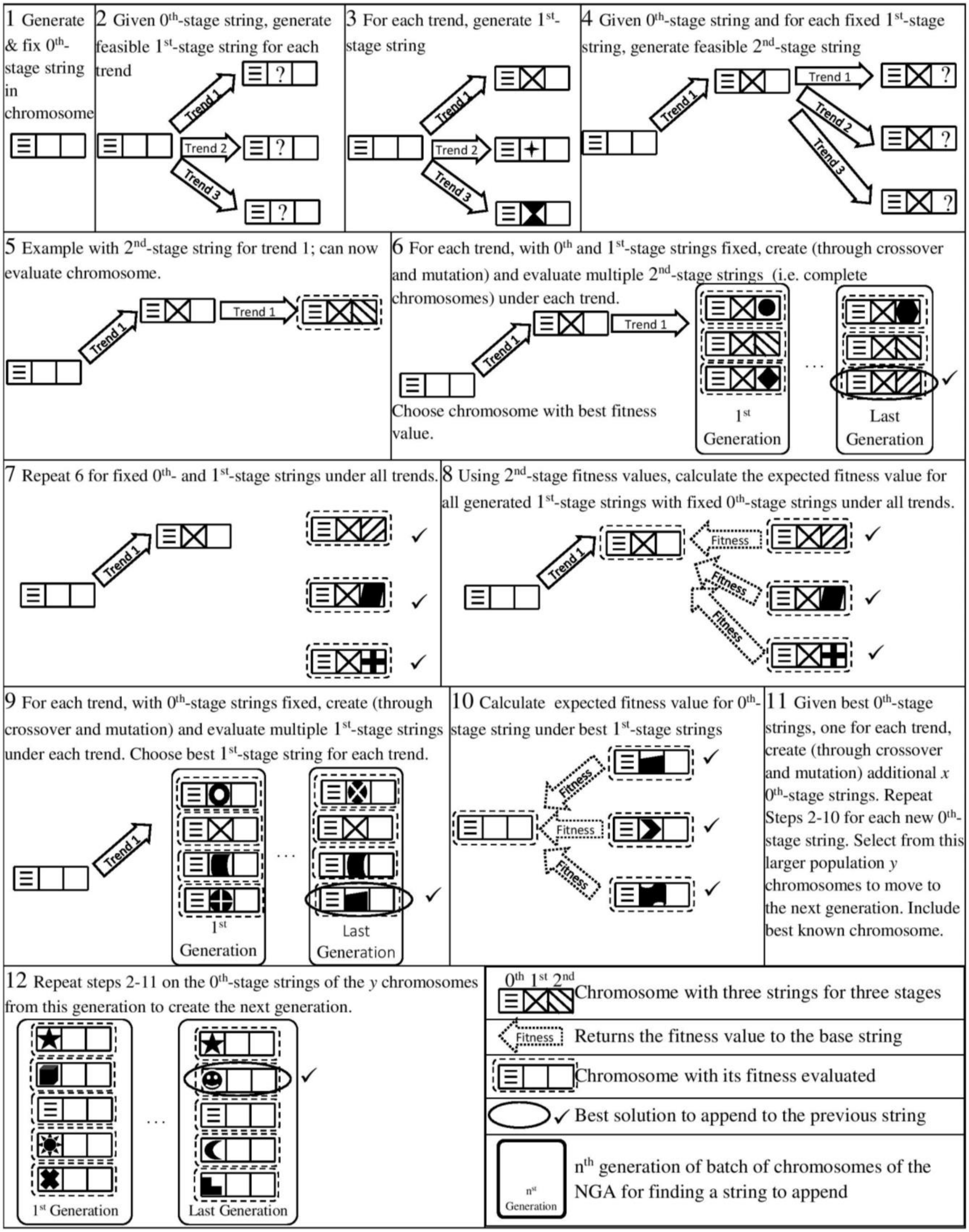

Figure 6. Rather than creating a single chromosome with a single string associated with each stage, a set of chromosomes, all identical in only the first string, with identical subsets in first and later strings, etc., are created.

Figure 7 illustrates the result of this process at which point the fitness of the first string (associated with the 0^{th}-stage) can be evaluated.

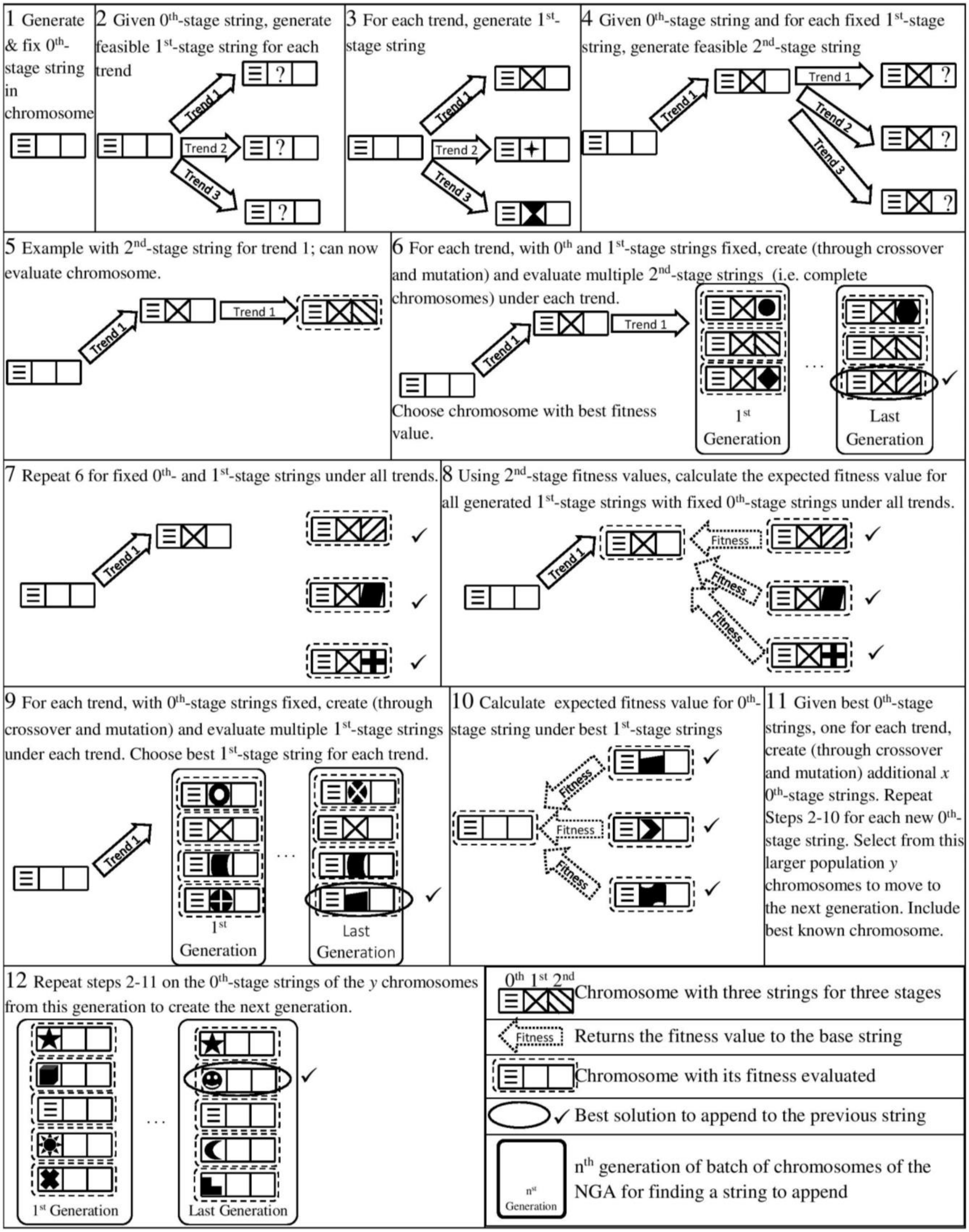

Figure 6: Steps of the rNGA Performed over Possible Scenarios

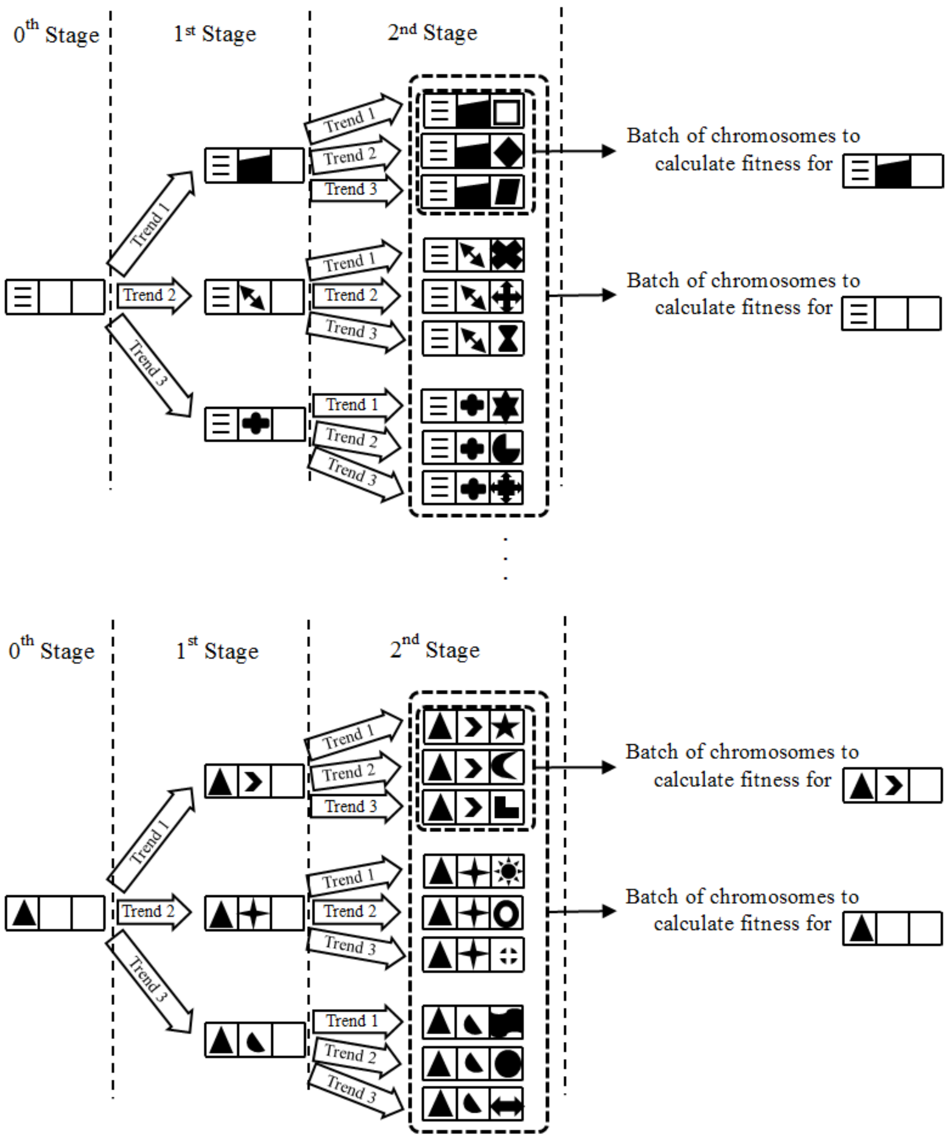

Figure 7: Multiple chromosomes generated with fixed 0th-stage decisions.

4.4 STEPS OF THE RNGA

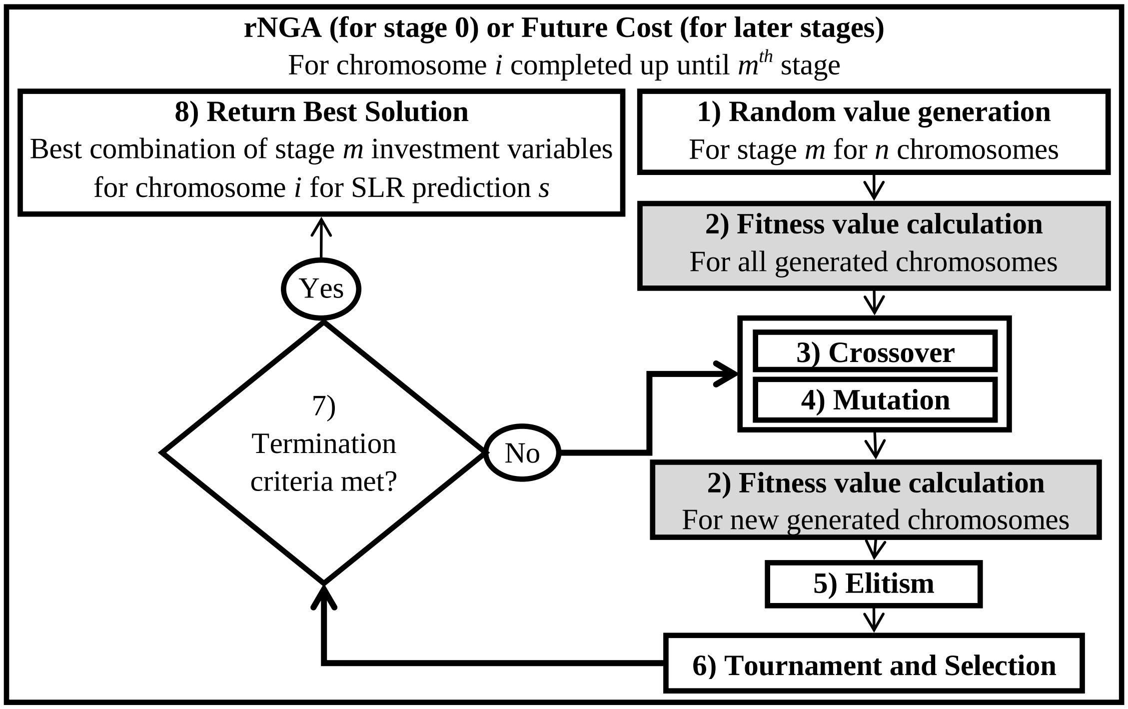

Figure 8 Steps of the rNGA

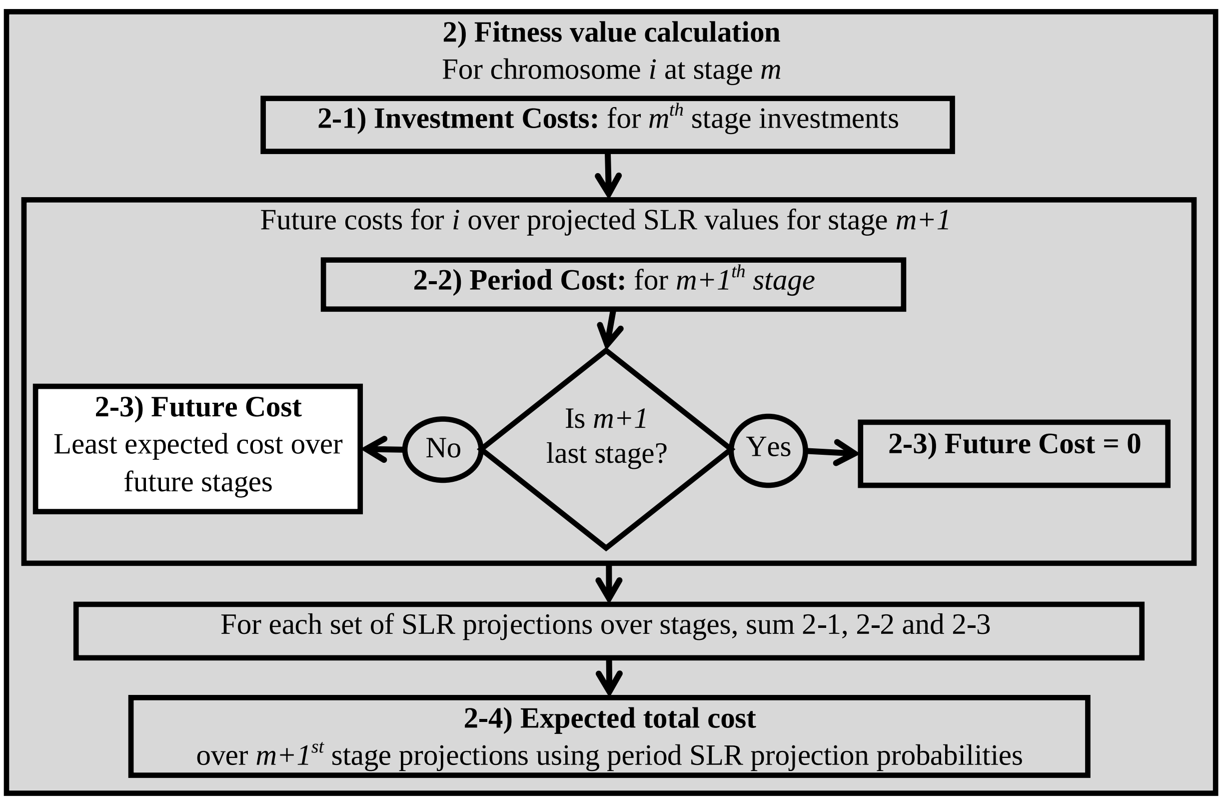

Figure 9: Fitness Evaluation Structure

4.4.1 Generation of initial population

For m=0, values for the 0th stage string are set randomly within their allowable bounds, building the first string to be used in creating the chromosomes. As mentioned previously, unlike more typical GAs where each chromosome in the initial population is created independently, this algorithm creates the chromosomes in batches, each batch of which has the identical randomly set stage 0 string. Figure 10 shows a sample chromosome with 0th stage random values.

	Stage 0				Stage 1				…	Stage $\|M\|-1$			
Link 1	0	2	0	0	-	-	-	-		-	-	-	-
Link 2	0	0	0	0	-	-	-	-		-	-	-	-
Link 3	0	0	3	0	-	-	-	-	…	-	-	-	-
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮	⋮
Link n	0	0	1	1	-	-	-	-		-	-	-	-

Figure 10: Chromosome with its 0th Stage String Values Set Randomly

For the case of m>0, building on decisions made in previous stages (0 to *m-1*), strings representing potential feasible decisions for the current stage are created. In their creation, maximum heights for building seawalls and raising elements and the existence of a drainage system constructed in previous stages are accounted for. Also, different from typical GAs, chromosomes are developed for specific scenarios, and scenarios are realized by stage. A rebuild decision in stage 1 is considered a possibility only if it is revealed after stage 1 that the associated infrastructure element has been destroyed. This process continues into stage 2 and later stages, where the realization of the scenario rolls forward with the stages. This construction process that depends on a rolling scenario realization framework is depicted in

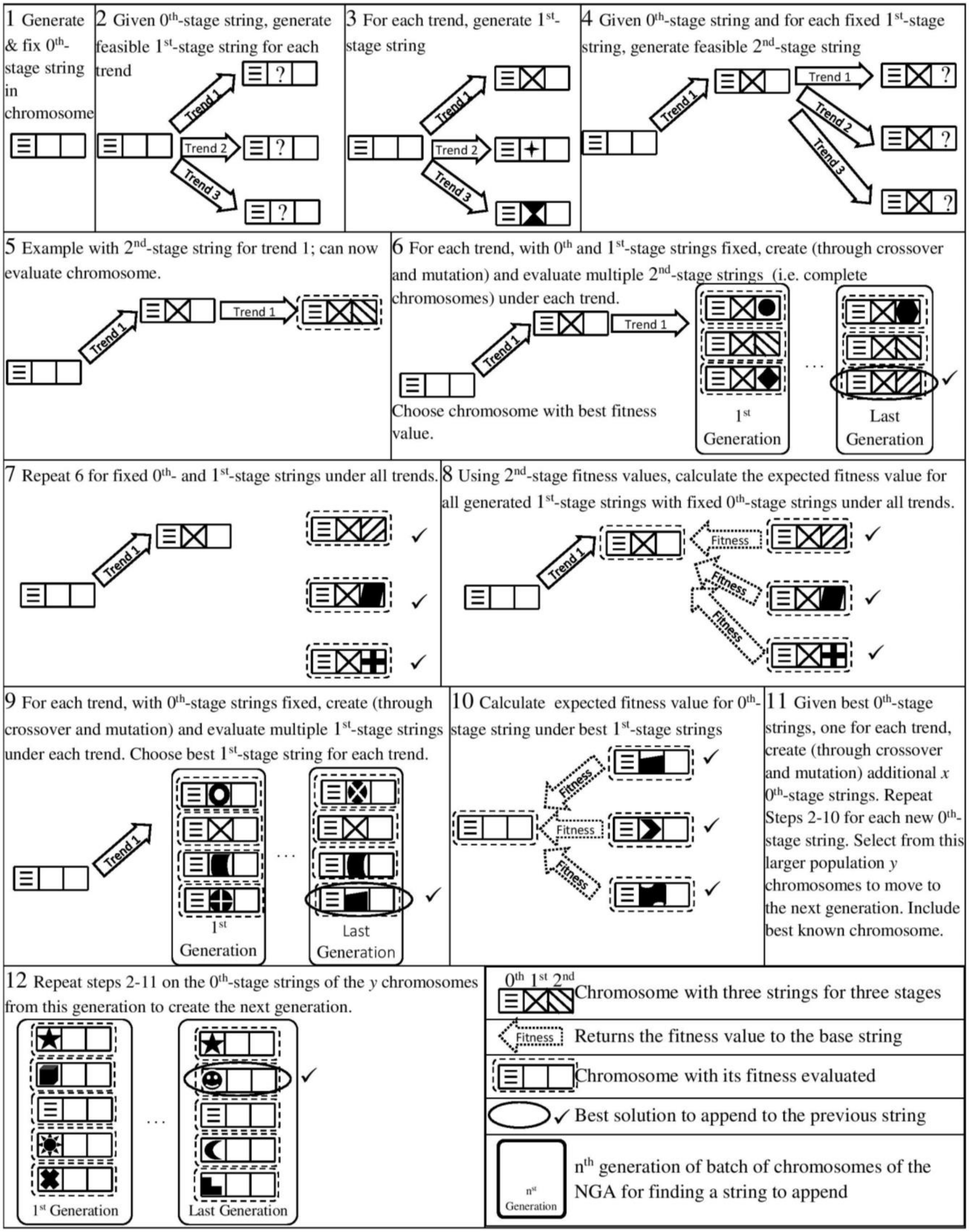

Figure 6.

Rebuild decisions require additional discussion. Rebuild decisions can be taken at any point in time after an element is identified as destroyed. It need not be taken in the immediate next stage. However, if an element is rebuilt in an earlier stage, there will be no value to rebuilding it again in a later stage if it is not destroyed a second time. Destruction of an element is assumed to arise as a result of multiple flooding events, each of which inflicts damage. The cumulative effect of these events is tracked.

4.4.2 Fitness value calculation

Fitness evaluation requires assessment of a recursive function, wherein the expectation for the end of the planning horizon can be determined based on chromosome performance under potential flooding scenarios associated with both SLR trend and episodic events. It assumes that the staged investment decisions are each taken optimally for future investments and responses to the episodic events occurring in the remainder of the planning horizon. Fitness evaluation rolls back from the end of the planning horizon to the present. Fitness is measured in terms of total direct investment (equation (7)) and response costs (equation (**Error! Reference source not found.**)), as well as indirect costs to travelers due to travel delays (lower-level objective function). Thus, to obtain the fitness value, the lower level UE problem must be solved for each realization of future conditions to estimate the required link travel times as part of the objective function. For this purpose, the Frank-Wolfe algorithm was implemented. An alternative Disaggregate Simplicial Decomposition algorithm with warm start was also tested; however, the Frank-Wolfe algorithm was found to perform significantly faster.

4.4.3 Mutation

For each stage (i.e. string) *m*, a predefined number of links are randomly selected for possible mutation. Each gene associated with the link is chosen for mutation based on a randomly generated number. If mutated, binary link values are flipped. If the value is to be altered from zero to a non-zero integer, a new value is generated that adheres to a maximum allowable improvement. This process is depicted in

(b)

Figure 11.

	Stage 0				Stage 1				...	Stage $\|M\|-1$			
Link 1	0	2	0	0	0	1	0	0		0	2	0	0
Link 2	0	0	0	0	0	3	0	0		0	0	3	0
Link 3	0	0	3	0	1	0	0	1	...	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮	⋮
Link n	0	0	1	1	0	0	0	0		1	0	0	0

(a)

	Stage 0				Stage 1				...	Stage $\|M\|-1$			
Link 1	0	2	0	0	0	1	0	0		1	2	0	0
Link 2	0	0	0	0	0	3	0	0		0	0	0	0
Link 3	0	0	3	0	1	0	0	1	...	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮	⋮
Link n	0	0	1	1	0	0	0	0		0	0	0	0

(b)

Figure 11: Mutation: (a) Original Chromosome (b) Mutated Chromosome

4.4.4 Crossover

Unlike typical GAs, crossover occurs during the construction and fitness evaluation process. At stage *m a* string is added to a base string from stages 0 through *m*-1 to create a new parent. Crossover involves two parents whose base strings (strings for stages 0 through *m*-1) will be identical. Genes for odd numbered links' are inherited from the first chromosome and even numbered chromosomes from the second chromosome. This process is illustrated in Figure 12.

The result is a new chromosome with identical values for previous stages as their parents but with a new combination of m^{th} stage values. This structure guarantees feasibility in the children if both parents are feasible.

Parents:

	Stage 0				Stage 1				…	Stage $\lvert M \rvert$			
Link 1	0	2	0	0	0	1	0	0		0	0	0	0
Link 2	0	0	0	0	0	3	0	0		0	1	0	0
Link 3	0	0	3	0	1	0	0	1	…	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮	⋮
Link n	0	0	1	1	0	0	0	0		0	0	0	0

	Stage 0				Stage 1				…	Stage $\lvert M \rvert$			
Link 1	0	2	0	0	0	1	0	0		0	2	0	0
Link 2	0	0	0	0	0	3	0	0		0	0	0	0
Link 3	0	0	3	0	1	0	0	1	…	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮	⋮
Link n	0	0	1	1	0	0	0	0		0	0	0	0

Child:

	Stage 0				Stage 1				…	Stage $\lvert M \rvert$			
Link 1	0	2	0	0	0	1	0	0		0	2	0	0
Link 2	0	0	0	0	0	3	0	0		0	1	0	0
Link 3	0	0	3	0	1	0	0	1	…	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮		⋮	⋮	⋮	⋮
Link n	0	0	1	1	0	0	0	0		0	0	0	0

Figure 12: Crossover

4.4.5 Elitism

A predefined portion of the chromosomes with best fitness values is maintained to move to the next generation.

4.4.6 Selection for next generation

Pairs of non-elite chromosomes are randomly selected for tournaments. Each chromosome is given a probability of selection based on its fitness value (those with lower values have higher selection probabilities). One from each pair is selected to continue to the next generation.

4.4.7 GA termination criteria

The procedure is terminated after a pre-set number of generations is reached or improvements no longer surpass a predefined threshold in relative fitness value reduction.

4.4.8 Identifying the best solution

Upon termination, the chromosome with the minimum fitness value (i.e. best performing chromosome) is chosen. The chosen chromosome provides the decision-maker with optimal or near-optimal first-stage actions given probabilistic information about future SLR-trends and episodic flooding events, assuming that decisions taken in future periods will be made optimally.

4.5 STAGE-DEPENDENT RNGA PARAMETERS

The number of chromosomes created in later stages would ordinarily grow exponentially with increasing stage. To avoid this, termination criteria, population size, number of mutations, crossovers, and generations, are set to be stage-dependent, growing smaller with increasing stage number. Accepting less and less accuracy in later time periods not only reduces the computational burden as future possibilities expand exponentially, but also reflects an acceptance of uncertainty in long-term predictive capabilities. Specification of the model parameters and chosen settings are provided in the next section.

5.0 CASE STUDY

5.1 EXPERIMENTAL SETTING

The proposed mathematical modeling and solution approaches were applied on a case study of a portion of the Washington, D.C. Metropolitan Area as illustrated in Figure 13. Critical roadways and national landmarks within the region are positioned at low elevations in close proximity to the Potomac River, and thus, are vulnerable to climate effects. Given the 3-foot typical high tide of the Potomac River, for only a six-foot rise in water, 21 miles of roadway in the area would flood (Strauss et al., 2015).

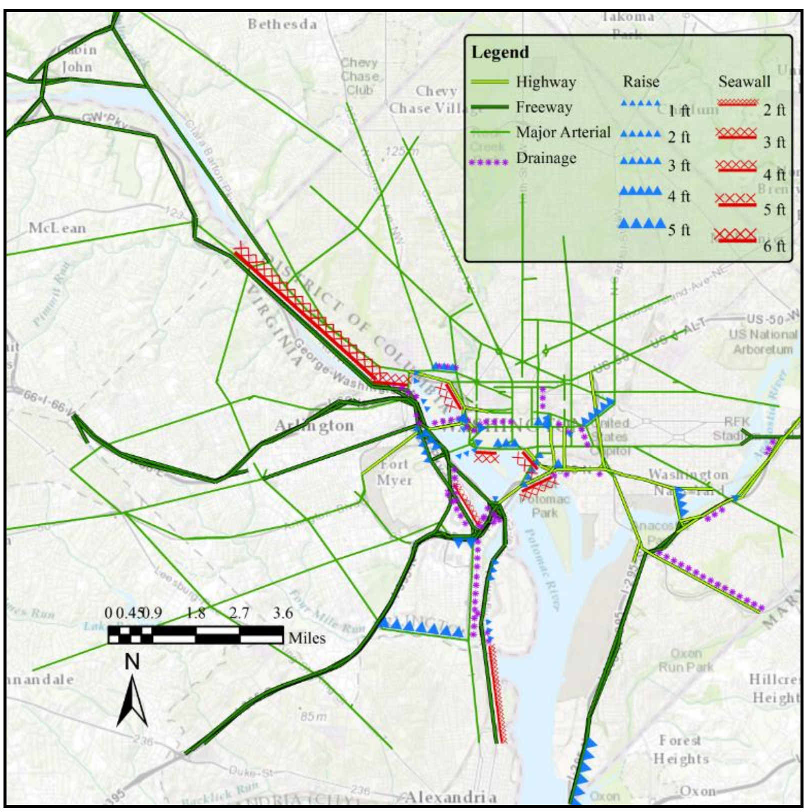

Figure 13: Location and extent of 0th-stage investment decisions in the network

The network representation of the roadway system in the study area includes the major roadways (freeways, highways and major arterials). Roadway data include the location, capacity, free-flow travel times and segment lengths. The data were extracted from Excel files made available through the Metropolitan Washington Council of Governments (MWCOG). The demand data for the extracted network was produced through DTAlite using OD demand from MWCOG data as input. Starting with 36,000 OD pairs, demand was spatially aggregated. The created network representation consists of 620 links, 1,122 nodes and 581 OD pairs. Roadway elevations in meters, referenced to the North American Vertical Datum of 1988 (NAVD88), were extracted from the National Elevation Dataset (3-meter resolution) for the same area. High tides over this datum have an approximate average height of 3 feet.

Three values of SLR predictions, representing the 5th, 50th and 95th percentiles, were obtained for each time period using the predictions for the midpoints of the respective stages. SLR predictions were extracted from the Climate Central website (Climate Central, 2015). Chosen values were calculated in the website using global sea level projections developed by Vermeer and Rahmstorf (2009) and further localized using the method given in Tebaldi et al. (2012). Associated with each point in time and each SLR prediction for that point, a set of four flooding (episodic) events (6 to 10 feet above high tide) were generated. Their associated occurrence probabilities were obtained from Climate Central (2015). A time horizon of 2020 to 2080, with midpoints at years 2030, 2050 and 2070, is assumed.

Four investment strategies for combatting the impact of SLR and other deleterious effects of climate change on the roadway network are considered as listed in Table 4.

Table 4: Cost estimates of mitigation strategy implementation

Project	*Cost*	*Per Unit*
Rebuilding	500,000	Lane mile
Seawall	1,000,000	Mile
Raising	1,500,000	Lane mile

Algorithm parameters and their settings are provided in Table 5. Parameters can be tuned for improved performance.

Table 5: Parameters of the rNGA

	Stage Number	**0**	**1**	**2**
Generations	Population Size	20	8	4
Termination	Maximum Number of Generations	10	5	3
	Minimum Acceptable Reduction in Fitness	0.05	0.07	0.1
Crossover	Number of Selected Chromosomes	6	4	2
Mutation	Number of Selected Chromosomes	3	2	1
	Number of Genes Considered for Alteration	20		
Elitism	Percentage of Elite Population	0.1		

An interest rate of 1.5% was used to convert future costs from different points in time to present value. α and β were estimated to be 109,500 and 36,000, respectively. A penalty coefficient of 20 hours for unmet demand resulting from disconnectivity is presumed.

5.2 RESULTS AND OBSERVATIONS

Three runs of the solution methodology were made: (1) a no-investment, no-damage, no-flooding case meant to provide a baseline for travel delay; (2) a no-investment, damage case; and (3) an investment-damage case. Subtracting the total cost under pristine conditions from the total cost in other runs eliminates costs due to baseline travel times.

Table 6: Results of the Case Study

Run #	**Possible Investments**	**Total Cost** ***$billion***	**Normal Travel Time** ***billion hr.***	**Flood Travel Time** ***million hr.***	**Total Investment** ***$millions***	**Unmet Demand** ***trips***	**0^{th} Stage Investment** ***$millions***
1	Pristine condition	717.4	-	-	-	-	-
2	No investment	1273.9	58	11.2	0	261.1	0
3	Full model	971.9	43	9.1	350.8	131.8	159.4

Comparing the total cost for runs 2 and 3 suggests that the cost of inaction exceeds the cost associated with preparedness, thus justifying the investment in reducing delays and increasing resiliency of the network against SLR and flooding events. In fact, the specific monetary benefits of preparedness can be quantified. A total of $302 billion in investments and travel time losses could be saved over the course of 60 years. Additional savings in unmet demand due to disconnectivity would also be realized. Benefits of investments stem from not only long-term, monetary return on investments, but more subtle societal welfare improvements.

Chosen investments under run 3 are depicted in Figure 13. $159 million of investment is made in stage 0 under this run. The investments include: providing seawall protection for 8 sections of links for a total of 8 miles of roadway, raising 26 link sections for 9.6 miles of roadway, and installing a drainage system along 35 roadway sections totaling 12.4 miles of roadway. Including investments made at later stages, the expected investment costs under this run would be $351 million in stage 0-valued dollars.

6.0 CONCLUSIONS

Solutions produced through the proposed optimization-based modeling and solution approach can help to answer a general and much debated question: Is there a need for costly actions, such as building sea walls, raising roadways, and relocating links, to combat sea level rise and prevent coastal flooding, or would it be more prudent to wait until after such an event arises to address subsequent damage? Application to the Washington, D.C. case study indicates the expected long-term payback and additional, indirect impacts that affect societal welfare.

The proposed methodology can be embedded within a decision support tool to aid governments, infrastructure owners, and operators in effectively addressing the threats from potential sea level rise and significant, sustained flooding events that will arise more frequently with increased occurrence of extreme weather events. By fixing model variables, the technique can also be used to examine the performance of chosen investments for a chosen time horizon.

Through minor modifications, the formulation and solution methodology can consider a fixed budget for taking protective or mitigative actions. The tool then can inform decision makers on the optimal investment of limited funds across subsystems, specific system components, regions or proposed projects.

Through optimal investment, the transportation network is made more resilient to future flooding events and, thus, safer and more reliable for drivers. By rebalancing terms in the objective function, more emphasis can be placed on investing to avoid flooding events with disastrous outcomes.

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