Ph.D. Dissertation of Engineering

Exploratory modeling of adaptation pathways to support decision-making for climate adaptation planning

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Exploratory modeling of adaptation pathways to support decision-making for climate adaptation planning

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Abstract

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Adaptation to climate change should be able to analyze the climate impact of future scenarios, identify potential adaptation options, and identify questions that may be raised in the policy-making process. Despite the growing importance of climate adaptation, there are relatively fewer and smaller scale adaptation policies implemented in response to climate change. The reasons for the lack of implementation are that it is difficult to predict the future, there is not enough information to determine the optimal adaptation measure, and there is no clear evaluation method to make final decisions. Furthermore, various stakeholders are involved in climate change adaptation policy-making and substantial costs with immeasurable benefits are common for many adaptation policies. Nevertheless, to persuade and gain support from various stakeholders when setting up an adaptation plan, policy evaluation data that can make rational decisions are needed. Therefore, to effectively implement climate change adaptation policies, a clear understanding of the policy and objective evaluation must be the basis, but policies are established based on qualitative judgments, and quantitative judgments of policy effects are not made.

The main goal of this study is to develop an exploratory planning model that can identify optimal adaptation pathways that achieve relative cost-effectiveness and effective climate impact reduction. Optimal adaptation pathways are selected if greater future damages are adapted and costs are lowered. Adaptation pathways for reducing impacts from 2020~2100 were generated as 16 consecutive 5-year plans referencing Korea's current adaptation planning period. At each 5-year planning time frame the scale for each adaptation measure was altered according to future impact level. To search for the optimal adaptation pathways, a machine-learning based evolutionary algorithm, the non-dominant alignment genetic algorithm (NSGA-II) was selected as the optimization method.

This thesis first introduces the developed adaptation pathway model, which is then applied to two decision-making problems. The two decision-making issues are 1) setting strategic goals and 2) prioritizing implementation tasks. In the first model application case, various scenarios are explored by mediating the preference of decision makers instead of fixing constraints and adaptation goals to preset values. In this case, direct adaptation measures (reducing the number of mortalities from heat risk) and indirect adaptation measures (improving the outdoor heat environment) were applied to reduce the number of projected mortality from heat stress. To explore goal setting options, various budgets and impact mitigation approaches were evaluated. In the second case, the adaptation pathway model is modified to accommodate different future mitigation policy target scenarios (RCP 2.6 represents the 1.5℃ temperature increase limit scenario, RCP 4.5 represents the 2℃ temperature increase limit scenario, while RCP 8.5 is the highest emission scenario).

The first application study found that after 2065, current adaptation strategies cannot reduce the impacts of heat mortality even with high budgets. A low budget limits adaptation for both ambitious and conservative goal settings while a higher budget did lead to greater adaptation but was not necessary for the conservative goal setting suggesting that efficient pairing of budget level based on the adaptation goal can be beneficial. Further, the longer the delay in investment toward adaptation results in irrecoverable reduction in adaptation.

For the second application case, the effectiveness and efficiency of green infrastructure-based adaptation technology was varied for reducing the impact of urban heat and flooding. When sorting the non-dominated optimized adaptation pathways according to sector prioritization, the most cost-efficient pathways were identified as optimal. The cost-efficiency was sensitive to future impact level and the cost trade-off of green infrastructure technologies. RCP 2.6 impacts were "too little" for current adaptation technologies to be cost-efficient relative to RCP 4.5 due to economies of scale. The increasing effects of green infrastructure-based technologies was difficult for the adaptation pathway model to consider under the RCP 2.6 scenario and resulted in under maladaptation before 2050 and over maladaptation after 2050. The effect of a social discount rate to green infrastructure-based adaptation was indirectly realized, where the cost subsidy provided additional resource to increase investment in non-green infrastructure technologies for the water sector.

The overall results of this study suggest the need to consider multiple dimensions in planning for adaptation and proves the benefits of using exploratory modeling as a base for clearer decision-making under uncertainty. The overall findings in this study fills the gap between research on adaptation pathway modeling and decision-based adaptation planning support tools. The results of both cases can be referred to when applying the decision-making method for adaptation planning.

Keyword: Climate change, adaptation planning, decision-making under uncertainty, optimization, maladaptation

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Publications

Please note that some part of this dissertation proposal was written as stand-alone papers (see below), and therefore there is some repetition in the methods and results.

1. Hyun, J.H., Kim, J.Y., Park, CY., Lee, DK. (2021). Modeling decision-maker preferences for long-term climate adaptation planning using a pathways approach. *Science of the Total Environment*, 772(1-2): 145335.

I. Introduction

Climate change already affects communities, and the impacts are projected to become more severe and intense in the future (IPCC, 2012). The benefits of implementing climate adaptation at the national and local level have been widely recognized with increased numbers of adaptation planning support tools provided by various actors (Giordano et al., 2013; ICLEI, 2010). Yet, the issues raised by climate change demand a long-term perspective and challenge traditional values and priorities in planning, which makes adaptation planning a burden for decision-makers (Carlsson-Kanyama et al., 2013). Many studies on the bottlenecks to effective adaptation planning and implementation have identified the difficulty in utilizing climate change science (Nordgren et al., 2016), limited assessment of local context (Cash et al., 2003; Dessai et al., 2009), lack of scientific evidence measuring the effect of adaptation measures (Rapley et al., 2014) and inadequate consideration of uncertainties, especially for long-term planning (Vij et al., 2017). These limitations have all hindered or discouraged ambitious adaptation efforts despite rising concerns and observed impacts.

Specifically, access to information in climate science has become very low (Dilling and Lemos, 2011; Lemos et al., 2012; Jones et al., 2015).

Increasing attempts have been made so far in terms of providing climate information so that such scientific information can be used in the planning and policy making process (Clar and Steurer, 2018). Climate services for adaptation planning support must define and frame the valuation of adaptation according to societal values and principles, regulations and norms and the state of knowledge (Gorddard et al., 2016). Adaptation can be effected as soft policies, physical implementation projects, and economic incentive measures. According to the defined problem frame, adaptation can a reactive or proactive response to a physical impact or social behavioral change indicator. Adaptation effect can cut across sectors (Berry et al. 2015) while multiple adaptation efforts can have synergistic or trade-off effects (Choi et al., 2021). Methods of evaluating adaptation also range from physical-based models to probabilistic and/or index-based evaluations (Bierbaum et al. 2013; Gorddard et al. 2016). The importance of relevant spatio-temporal data is continuously mentioned as a limitation to effective decision-making for adaptation planning (Preston et al., 2011; Woodruff and Stults 2016).

To mediate the burdensome task of long-term adaptation planning, recent support tools suggest using the concept of “adaptation pathways” to systematically sequence adaptation solutions across a long timeframe (Haasnoot et al., 2013; Kwakkel et al., 2016). Adaptation pathways is among the many analytical frameworks for decision making under uncertainty (DMDU). These approaches are unique in their framing and method of considering the deep uncertainties according to the various decision-making components such as, generation of scenarios, robustness metrics, sensitivity analysis, etc. (see Kwakkel and Haasnoot., 2019).

The primary aim of this study is to develop an exploratory planning model that can identify a Pareto of optimal adaptation pathways that achieve relative cost efficiency and effective climate impact reduction. Exploratory modeling refers to discovering alternative designs under conditions (i.e. combinations of values of uncertain factors defining scenarios) that no longer achieve satisfactory performance (Maier et al., 2016; Quinn et al., 2020). This process is also called "scenario discovery," where n-way sensitivity analysis or factor-mapping of sensitivity is conducted (Herman et al., 2015; Moallemi et al., 2020). From this process, decision makers can identify when to adapt their current systems to avoid the scenarios of failure. Rather than fixing the constraints and adaptation goals to preset values, this study explores different scenarios that capture decision-maker preferences not yet modeled in previous studies. The model is applied to reducing heat-wave related mortality as well as reducing multi-sector impacts on the urban scale in South Korea. Multiple adaptation strategies that either directly reduce the impacts (prevent human deaths and capture stormwater) or indirectly by reducing the cause of the impacts (mean radiant temperature (MRT) to create thermally comfortable urban areas and rainfall interception to reduce stormwater runoff) are modeled. The vast range of possible adaptation pathways were searched and evaluated using a multi-objective optimization method, Non-dominated Sorting Genetic Algorithm, NSGA-II (Deb et al., 2002).

This thesis introduces the adaptation pathway model to apply it to two decision-making problems. The two decision-making problems are based on frequently mentioned challenges to adaptation planning – strategic goal setting and prioritizing options. To explore goal setting options, the cost-benefit of different budgets and impact reduction approaches to avoid maladaptation is assessed for the case of Seoul in reducing urban heat risk impacts under RCP scenario 8.5. For the seconds case, adaptation pathway model was altered to assess multi-sector risks according to the different future mitigation policy goals/scenarios (RCP 2.6 indicates a 1.5℃ increase limit, RCP 4.5 indicates a 2℃ increase limit, RCP 8.5 indicates the highest emission scenario). The trade-offs and co-benefits of green infrastructure (ecosystem-based adaptation) were highlighted when applied to reduce the impacts of urban heat and flood risk. The overall flow of this thesis is summarized in the figure below:

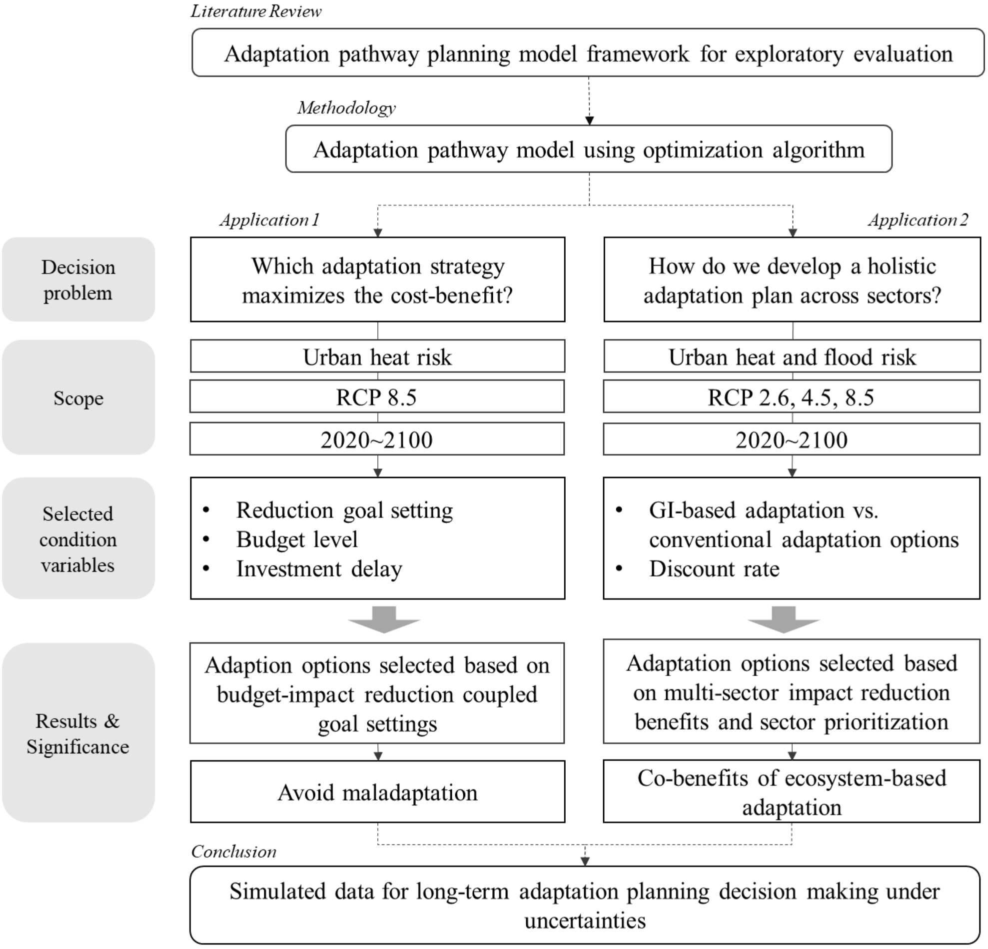

Fig. 1. Study flow

This study fills the gap between the research on adaptation pathway modeling and decision-driven adaptation planning support tools. The model introduced in this study can involve decision-makers to direct their search for optimal adaptation pathways with visual explorations of repeated and simultaneous assessments of their preferred needs and constraints. Results from the two cases can be used as references when framing decision making methods for adaptation planning. By indicating the model’s limitation and methods for improvement, the implications of this study and future studies are proposed in the discussion and conclusion.

II. Literature Review

1. Challenges in decision-making for adaptation planning

Decision-making refers to all processes in which decision-makers set criteria for judgment when writing an implementation plan and make choices among various alternatives. That is, the process of identifying viable alternatives and selecting countermeasures. Decision making is part of the planning process, which starts with problem identification and ends with making choices. Planning and decision-making are closely related, where decisions can be made without a plan, but a plan cannot be completed without a decision. The planning elements included in the decision-making phase in practice consist of 1) information collection and analysis, 2) problem definition, 3) goal setting, and 4) implementation task selection (Lee, 2018).

In recent adaptation studies, research on “decision making” is increasing (Wise et al., 2014). Early adaptation planning decision-making studies identified drivers and barriers of adaptation, evaluated vulnerability and adaptation capabilities, identified adaptation policies in specific situations, and created adaptation opportunities (Burch, 2010; Moser and Ekstrom, 2010; Ford and King, 2015). Recent research has been conducted to help decision makers select urgent policy options in complex social structures and environments (Eakin and Patt, 2011), mainly in the long term. The focus is on the development of techniques or tools to address uncertainty and a wide range of decision-making processes (Dessai and van der Sluijs, 2007; Ranger et al., 2010; Weaver et al., 2013).

Studies have highlighted the importance of adaptation plans to have a systematic feedback loop from problem setting, sector planning to monitoring and evaluation of plans. The decision-making process must be carried out in consideration of this feedback loop, taking a holistic approach to planning which requires the following information and tools (Figure 1).

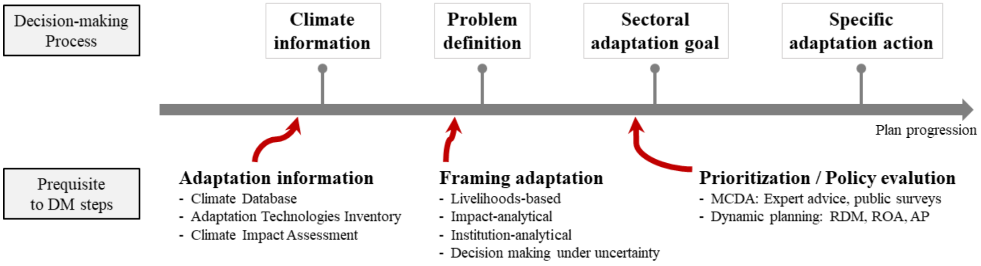

Fig. 2 Prerequisites for effective decision-making in adaptation planning process

To set a specific goal, quantitative impact assessment and adaptation countermeasure technology evaluation are carried out to evaluate whether the set goal can be achieved. According to Young et al. (2019), rather than applying long-term climate information to plans, stakeholders tend to prioritize current risks and urbanization issues and take into account extreme events that may arise in the future. Extreme climatic phenomena are important catalysts for many adaptive actions, while climate change itself is rarely a motive alone (Berrang-Ford et al., 2011; Ford et al. al., 2013). From a scientific point of view, extreme climate information can be a useful indicator when suggesting an underlying climate trend (Travis, 2014). But false assumptions that the frequency or intensity of such extreme climates will increase, may lead to maladaptation or further increase vulnerability in the future (Barnett and O'Neil, 2010).

It is also important to identify potential problems that hinder adaptation, but it is difficult to say that they are helpful as the impeding factors do not tell how to solve problems in the planning and decision-making process (Wise et al., 2014). In order to diagnose the 'problem' well and to suggest a solution, communication, participation, and negotiation must be conducted in a legal and fair process (Striling, 2006). Through communication in the adaptive framing process, a clear problem description and subsequent goal setting for decision-making within a complex social system can be performed.

When implementing an adaptation plan, it is important to establish an efficient adaptation plan because resources such as financial resources, manpower, and time are limited. For this reason, it is necessary to evaluate the adaptation measures to determine which measures should be implemented and to prioritize them. There are various methods for evaluation, and the most commonly used techniques are CBA (Cost Benefit Analysis), CEA (Cost Effectiveness Analysis), and MCA (Multi-Criteria Analysis). The MCA includes the evaluation of adaptation options according to quantitative and qualitative evaluation criteria and allows the evaluation to be carried out participatively. According to UNFCCC (2002), when evaluating climate adaptation measures, 1) various evaluation criteria and indicators must be considered, 2) it is difficult to calculate the cost of climate change in monetary terms, and 3) The perspective must be considered. To meet these conditions, MCA is the preferred method of evaluating adaptation options and policies (Kubal et al., 2009; de Bruin et al., 2009). However, a static assessment of adaptation options may not be sufficient for adaptation measures that require long-term planning, such as long-lived large infrastructure projects such as drainage, dam or breakwater construction. In some cases, you will want to avoid crossing thresholds, such as extinction of certain species. Moreover, as extreme events are becoming more frequent and stronger due to climate change (IPCC, 2012), it can be said that the time to intervene has come. Accordingly, a planning method that can adequately evaluate the evaluation of long-term adaptation options is needed (Vervoort et al., 2014; Woodward et al., 2013; Beh et al., 2015).

2. Valuation of adaptation benefits

Defining adaptation and its basic goals remain a topic for research as it is "contingent upon the events or conditions to which it is reacting or anticipating" (Owen, 2020). The goal of adaptation can be defined as either increasing adaptive capacity, increasing resilience, or reducing vulnerability (Yamin et al., 2005). Dessai and Hulme (2007), de Bruin et al. (2009b) and Hof et al. (2009)'s suggested approach to accounting for adaptation benefits includes the consideration of the costs spent for adaptation against the gain in reduction of damages (residual cost of climate change) and increases in climate-related welfare. Another commonly used definition of adaptation as adjustments in human systems in response to actual or expected climatic stimuli or their effects, which moderate harm, offers little practical guidance to valuation of adaptation. While some adaptations may be framed to specifically address climate change related impacts (e.g. hard infrastructure projects), adaptation often involves policy, institutional, legal and financial responses to reduce sensitivity and increase adaptive capacity (Ford et al., 2013).

Characteristics of success need to be identified to define the effectiveness of adaptations in reducing vulnerability as some adaptation measures may have direct and measureable outcomes, while in many instances impacts on vulnerability may not be directly visible and/or will be evident only over many decades, with different interpretations on what characterizes success. For example, under process-based/adaptation readiness effectiveness measurement, key governance factors essential for effective and successful adaptation is taken into account.

Meanwhile in integrated assessment models, the multi-dimensionality of climate adaptation is simplified as an economic damage function to provide estimates of the economic costs that would occur for absolute changes in global temperature. This in itself is a limitation where the only climatic factor considered is limited to global annual mean temperature rise (Liu et al., 2019). Agrawala et al. (2011) examined how global and regional costs and benefits of adaptation are assessed and incorporated in three integrated assessment models. Their study was the first attempt in comparing results on adaptation costs by subdividing into reactive adaptation, "stocks" and investments on building adaptive capacity. Recent studies have begun to investigate theoretical ways to alter and adjust the damage function to be considered dynamically, as a function of time instead of a fixed quantity (Estrada et al., 2019) and fitting the damage function on net impacts (Diaz and Moore, 2017). Quantifying the benefits of adaptation remains a challenge in theory and in practice and thus no common definition and method.

3. Exploratory modeling for decision-support

The common principles of effective decision support proposed by the IPCC are as follows. It should be made according to the user's demand, not the scientific research priority, and the user's demand can be identified through discussion between the user and the researcher. In addition, by pursuing institutional stability, it is possible to secure necessary trust and familiarity by efficiently linking users and producers. Therefore, all parties should be able to recognize and contribute to the need for “structural decision support that enables flexibility, adaptability and learning through experience” (IPCC, 2014). In Korea, information and tools supporting the decision-making stage are still distributed, so it is difficult to construct an integrated system that supports decision-making based on an adaptation path. It is difficult to make climate change decisions in that decision makers have different expertise and capabilities in dealing with extensive and complex climate change information, and that various alternatives can appear as they reflect regional characteristics (Howarth and Painter, 2016).

In the use of climate services, it was found that related policies and establishment obligations play a major role. Policy allows future climatic conditions to be integrated into day-to-day work, which inevitably changes the state of the current process (Tart et al., 2020). In the case of Korea, each local government is obligated to establish an adaptation plan, which is important in that the demand for climate services is particularly high, and it intends to actively utilize it for adaptation to climate change. The climate service sector was created to respond to the fact that improving climate information and decision support tools does not always lead to effective adaptation. Climate services recognize that usable and useful information can be tailored and provided in a timely manner and used to increase the likelihood of adaptation (Vincent et al., 2018). They must meet user needs, capacities and decision-making frames (Vaughan and Dessai, 2014) and cannot be universally applied due to various prerequisites, regional characteristics, and the presence of relevant stakeholders (Cotekar et al., 2016).

Climate services developed to address and identify climate change adaptation plans require an understanding of the decision context and the specific decisions that climate services can handle. It should also be able to encourage and mediate the collaborative process between people with different needs and knowledge backgrounds. Finally, flexibility must be gained through continuous knowledge exchange, monitoring and learning, which can be used to improve and update product and service processes

(Vincent et al., 2018). Williams et al. (2020) stated that the utilization of climate information will be amplified if climate services are provided according to the capabilities of users. Therefore, climate services should be provided so that predictions and results based on scientific results can be tailored to user needs and capabilities to aid in decision-making and policy planning (Larosa and Mysiak, 2019, Palutikof et al., 2019).

New planning approaches and methods of assisting these approaches have been put forward in response to these challenges. Many of these approaches assume and predicate a certain or series of potential futures and these scenarios are quantifiable according to predefined definitions of the correlations and causations of the futures and adaptation methods (Weaver et al., 2013). The limitations of these approach settings are highlighted in the difficulty to translate into practice due to limited information and inapplicability to different contexts of the problem. The infrastructure planning field has relatively benefited overall from these approaches as they have a long life time, alter according to future conditions and predictions, bring together a variety of stakeholders and depend on the geographical scale contexts (Kwakkel and Van Der Pas, 2011; Weaver et al., 2013; Herman et al., 2020).

Exploratory modeling and analysis is a method that can support exploration of sets and ranges of plausible parameter values and draw valid inferences from the exploration. Simulation gaming is similar in procedure and approach for exploratory modeling as it does not assume that existing knowledge about a system is to be used to analysis under a surrogate real world system (Kwakkel and Van Der Pas 2011; Weaver et al., 2013; Quinn et al., 2020). For example, in Quinn et al. (2020), six parameters to determine which conditions most influence users' water needs and to map what combinations of parameters lead to unsatisfactory performance was explored using exploratory modeling. They suggest working collaboratively with system experts and stakeholders to identify major uncertainties that might influence the performance of the system under evaluation (Marchau et al., 2019).

A direct application of the exploratory modeling approach can begin with the use of RCP scenarios as suggested by Weaver et al. (2013) – rather than using projection and scenarios as predictions of the plausible futures, adopting functional definitions and approach to using the prediction to support actual planning decision and how using one set of predictions over another would differ. The most common approach to identifying multiple plausible futures is arguably the use of scenarios, “possible future states of the world that represent alternative plausible conditions under different assumptions" (Mahmoud et al., 2009). Scenarios must therefore represent coherent storylines based on different assumptions of the future. Scenarios can be divided into predictive – what will happen, explorative – what could happen, normative – how can a specific future be realized (Maier et al., 2016).

4. Decision-making under deep uncertainty

There are many analytical frameworks for decision making under uncertainty including, real option analysis (Beh et al., 2015; Trindade et al., 2017) – calculates the value of an option's implementation against the no-action scenario, robust decision making (Lempert et al., 2006; Bhave et al., 2014; Reis and Shortridge, 2020) – stress test the various possible options to the future to identify robust strategies, and portfolio analysis (Trindade et al., 2019) – evaluating a fixed set of options against uncertain conditions. Recent work on decision making under deep uncertainty seeks to find alternative infrastructure designs, or policies for managing that infrastructure. These approaches are unique in their framing and method of considering the deep uncertainties according to the various decision making components such as, generation of scenarios, robustness metrics, sensitivity analysis, etc. (see Kwakkel and Haasnoot., 2019).

Table. 1 Approaches to support DMDU

Approaches	Description	Main Characteristics	Key references
Scenarios-based	Key focus on alternatives within a system and set process	Inflexible; case focused, Local, national and global scale	Moss et al., 2010; Vervoort et al., 2014
Real option analysis	Treating a range of adaptation options as ‘real options’ in the face of uncertainty and evaluating the merits of both action and inaction in this context	Flexible; uncertainty; case focused	Yang et al., 2008; Woodward et al., 2013
Portfolio analysis	Selecting a portfolio of adaptation options rather than single options and exploring which is most effective in terms of return and uncertainty	Flexible; experimental; uncertainty	Beh et al., 2015
Robust Decision Making	Quantitative decision-analytic approach for supporting decisions under conditions of deep uncertainty and informed by stakeholder driven processes	Flexible; uncertainty; stakeholder engagement	Lempert and Groves, 2010; Weaver et al., 2013
Adaptation Pathways	Key focus on policy reflexivity and adaptive nature of it. Emphasizes policy and transformational change; conceptually and theoretically in experimental phase, but some empirical evidences at local scale available	Flexible; reflexive; time-oriented; experimental; focuses on incremental change; deep uncertainty	Butler et al., 2016; Wise et al., 2014; Hassnoot et al., 2013

Adapted from Vij et al.. (2017) and McDermott and Surminski (2018)

Real Option Analysis (ROA) evaluates the right time to invest. It is suitable for decision-making because the results of the technology evaluation are different depending on the timing of application of adaptive technologies that require large-scale investment (Buurman and Babovic, 2016). However, this method has a limitation in that the interaction and synergy between options are not considered because the plan is established only with the results of individual analysis for each option. One that can overcome this is Portfolio

Analysis (PA), which is based on diversification, which helps to develop a list of options rather than a single option. This method is not widely used in climate change adaptation planning because it cannot be used for long-term planning because the temporal factor is not considered. Robust Decision Making (RDM) is used in situations where there is high uncertainty, that is, in situations where there is no probabilistic information about scenarios and outcomes. RDM identifies the optimal options based on economic efficiency, and uses data mining algorithms or metric models to evaluate how strategies are performed in various scenarios that reflect future situations.

Recent climate change adaptation planning research aims to deviate from a scenario-based, 'predict and plan' framework to a policy approach that considers uncertainty and encourages long-term 'learning by doing' (IPCC, 2012). Adaptation pathways can be suggested as a suitable method. For long-term planning, it is important to be able to select the most effective adaptation measures and techniques according to the changing conditions from time to time. Therefore, it is necessary to evaluate the adaptation effect in advance according to the timing of implementation of the adaptation measures.

Adopting a pathways approach allows for strategic rather than reactive planning using signals and triggers for timely implementation of adaptation actions (Haasnoot et al., 2018; Stephens et al., 2018), especially for the long-term while considering the short-term constraints (Walker et al., 2013). Such sequential planning approach can help identify when and which adaptation options need to be adjusted to avoid maladaptation while considering multiple possible futures (Kwadijk et al., 2010; Wise et al., 2014). Since pathways are drawn by calculating when and which preceding action is no longer effective, decision maker judgements and evaluations are intrinsic to the process, thus applications are suggested to include active participation while tools must consider the user's decision making process (Bosomworth and Gaillard, 2019). Adaptation pathways has been applied in various fields (e.g., water management, agriculture, infrastructure planning, energy systems design) with increased data availability on climate change impacts and their uncertainties as well as the biophysical and economic effects of adaptation options across futures scenarios (Babovic and Mijic, 2019; Beh et al., 2015; Cradock-Henry et al., 2020; de Ruig et al., 2019; Kingsborough et al., 2017).

The purpose of the adaptation pathways approach is not to provide one optimal plan as a result, but to show the feedback process of decision-making, which is expressed as uncertainty and dynamic long-term planning in the process of deriving the path plan. Figure 2 is a simplified representation of the characteristics of the adaptation path. The x-axis represents time, the y-axis represents the impact of climate change, and the impact is the impact of one sector or multiple sectors. The adaptation path can be plotted against a "no-action taken" path and a safety threshold, which is the minimum criterion for adaptation. The adaptation measures expressed in circles can be one or several policies/techniques, and the scale of introduction of policies/technologies can also be specified, and the effect of reducing the impact depending on the time of application can be known. Various adaptation paths expressed in this way can be compared and analyzed.

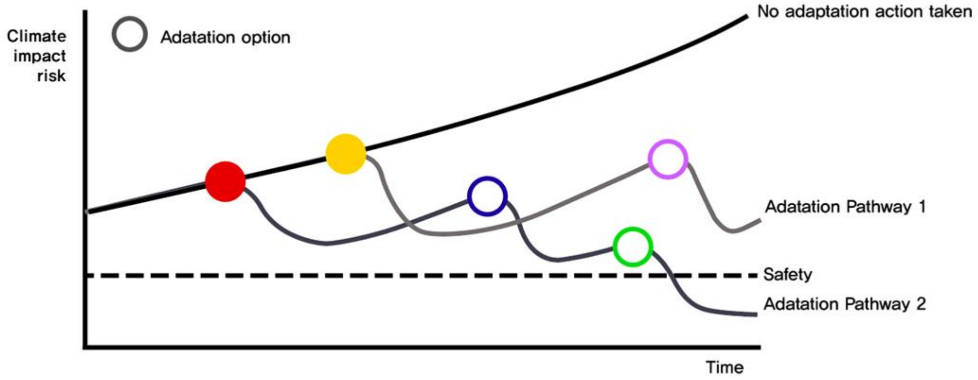

Fig. 3 Conceptual drawing of adaptation pathway (Susaki and Kubota 2017)

Many adaptation pathway application studies consider the suitability of adaptation options according to fixed objectives with advanced quantitative evaluation of their economic and engineering values. Most follow the traditional scenario analysis method where the uncertain states of the world are predefined based on selected scenarios and thus often inadequately capture decision-maker preferences (Herman et al., 2015). The use of models is useful for posteriori, exploratory decision-making support purposes. Models can conduct different computational experiments to simulate how the various uncertainties might formulate (Kwakkel, 2017; Walker et al., 2013). A fundamental aspect of the decision-making process is designing the alternatives to generate different possible preferred pathways (Babbar-Sebens et al., 2015; Haasnoot et al., 2013). Applying heuristic search algorithms reduces the computational requirements by retrieving and storing information with the help of information technologies (Babbar-Sebens and Minsker, 2012; Shah and Oppenheimer, 2008).

Further benefits of using meta-heuristics to solve nonlinear problems include flexibility in designing, guiding and computing multiple, complex performance objectives (Woodruff et al., 2013; Quinn et al., 2017; Bartholomew and Kwakkel, 2020). In addition, the application of multi-objective optimization has allowed for more holistic and accurate representation of solutions to various climate adaptation decision-making problems by independently considering the different goals in search for optimal alternatives (Kasprzyk et al., 2013; Kwakkel et al., 2015; Yoon et al., 2019). One commonly used type of meta-heuristics, evolutionary optimization algorithms have been used to draw many adaptation pathways to address various climate change impacts (Beh et al., 2015; de Ruig et al., 2019; Tanaka et al., 2015; Yoon et al., 2019). Thus, decision makers can benefit from decision support systems that can translate science to policy and vice versa, incorporate both scientific and local knowledge, and ultimately integrate the exploration of ideas with participatory and direct evaluation in real time (Basco-Carrera et al., 2017; Zandvoort et al., 2017).

In consideration of these needs, the model in this study aims to be used as an exploratory modeling tool to simulate various decision-making variables to assess climate adaptation strategies for the long term and fill the gap identified in previous studies. First, it is necessary to define a problem appropriate to the local situation under the agreement of decision makers, and a clearer goal should be established based on this. Second, the evaluation of scientific adaptation measures should be built in accordance with the characteristics of the region, and information should be properly delivered to local decision makers. Otherwise, a decision is made with an information deficit approach without evaluation of whether the information for problem-solving is verified or meaningful (Cash et al., 2002; Brunsson, 2007). Therefore, it is necessary to first grasp what information is needed for decision makers, and data with objectivity that can be used socially in the subsequent evaluation of adaptation measures should be constructed.

Finally, it is necessary to cope with the uncertainty of future climate change by allowing decision makers to construct flexible adaptation measures based on the adaptation path including the long-term future. Specifically, the effects and costs of applying the adaptation policy can be presented, which helps local decision makers understand and suggests a proposal for consultation among various stakeholders. In addition, it is possible to propose a strategy that can take into account mid- to long-term planning and implementation capabilities of the target site. These strategies can be used as useful data in the future implementation evaluation and monitoring phase.

The most important decision support information that can be used are customized climate change impact/vulnerability assessment reflecting local conditions. Even though the results for each scenario are provided, it is difficult to reflect them into the adaptation target because the results of the effectiveness evaluation on how much damage they can cause are not clearly stated, and this makes it difficult to follow existing projects. If scientific information-based quantitative effect evaluation can be made, a highly effective adaptation plan can be established, and for this, a systematic information collection-supply system must be provided. In addition, it is difficult to establish customized plans for target sites with the generalized adaptation policies and support systems (guidelines, manuals, case books) currently provided in Korea, and needs to be supplemented according to the evolving decision-making process and planning method. To support the decision-making of selection, evaluation and implementation evaluation of adaptation measures, objective tools should be provided. In particular, it is necessary to cover concepts such as risk evaluation, impact assessment in addition to vulnerabilities, and to determine adaptation goals according to local governments' adaptive capacity. This study aims to serve as one of these tools.

In the following section, the scope of this study, especially the selected variable conditions to search for optimal and sub-optimal adaptation pathways are explained.

III. Scope of study

The context for this study lies in the unique case of Korea, where local governments, who have the responsibility of establishing adaptation planning every five years, depend on national support tools and guidelines yet these methods and information provided are not useable without a certain level of local government's resources and capabilities. For example, in the case of climate scenario data, the Meteorological Administration provides it, but since expertise is required to process and utilize future climate information, it is distributed in the form of a report to each local government. As a tool for evaluating impact and vulnerability in Korea, the Local government Climate Change adaptation toolkit based on GIS (hereinafter referred to as LCCGIS), which evaluates the relative vulnerability of sub-regions based on the local government as a base unit in the early stages. CCGIS), and after that, a web-based Vulnerability assESsment tool To build climate change adaptation plan (VESTAP), developed to overcome the limitations of LCCGIS, which does not reflect regional characteristics, was created (KACCC, 2019). VESTAP was created to provide basic reference data for adaptation measures, and evaluates vulnerability defined as a function of climate exposure, sensitivity and adaptive capacity according to standardized climate change scenarios (Oh et al., 2017), and the scope of the evaluation area. The evaluation results differ depending on the composition of indicators and weights (KACCC, 2019).

In fact, the difficulties and obstacles that they face in the establishment process in using climate information can be confirmed in the implementation evaluation statement included in the secondary adaptation measures of the metropolitan local government. The implementation of the first adaptation measures of the metropolitan local governments was completed for 5 years, and the implementation evaluation was made. Each local government prepared and submitted a report on the implementation of adaptation measures every year through the process of collecting opinions from the relevant departments for each detailed project from the Climate Division, which is the department in charge of establishing adaptation measures. The evaluation of the 1st detailed implementation plan is described in the 2nd countermeasure by combining the implementation evaluation over four years and looking at the content reveals obstacles and difficulties in planning, including the content of the implementation evaluation (MOE, 2020).

Problems identified in the planning process of each local government can be divided into four broad categories. The first is that policy makers have low awareness and consciousness about adaptation to climate change. For this reason, policies from similar sectors are drawn rather than climate change adaptation measures, and policies are established by confusion of concepts such as climate change adaptation, disaster prevention, and environmental conservation. Apart from the problem of professionalism in person in charge due to rotational positions, there is a difficulty in not contributing to the spread of climate change adaptation awareness and conscious policy establishment as education on climate change is mostly focused on GHG reduction and related contents. Second, the plan may vary depending on the expertise and competence of the working staff. Due to the nature of the manpower arrangement of public officials, there is a problem that the job continuity is cut off due to frequent replacement of officials in charge. In addition, since it is difficult to obtain information related to climate change adaptation in a short period of time, it is difficult to take over, and if an adaptation plan is established in such a situation that lack of information, the validity of the plan may be questioned. Third, there is a lack of analysis of the impact and vulnerability analysis and the surveyed climate data. Relative vulnerability results according to future climate scenarios are expressed using analysis tools such as VESTAP, but it is not revealed how they are related to the list of adaptation targets or adaptation countermeasures, and how they are interrelated. Since the use of information is insufficient, the collection-supply system of information is also insufficient.

Within this context, the aim of this study is to formulate applicable exploratory cases from the perspective of Korea’s local adaptation planning decision-makers. The following explanations guide the approaches taken for the study cases in this thesis.

1. Setting adaptation goals according to decision-making preferences

The method and materials used to find optimal adaptation pathways include a range of input data, selected scenario variables and the optimization search algorithm. In the first problem case, the impact and adaptation effect values used in this study are based on heat-wave related mortality according to RCP scenario 8.5 in Seoul, South Korea. Many studies expect that cities will endure increased extreme heat events (including heat waves) in the future (Chapman et al., 2019; Founda et al., 2019). Cities in Korea are no exception and thus vulnerable to increased frequency, magnitude, and duration of hot events in the future (Min et al., 2015).

For the purposes of our study, we based our analysis using one future climate scenario (RCP 8.5) in order to focus on assessing the effects of decision-maker’s economic preference (budget level and investment delay) and risk preference (adaptation goal) in achieving adaptation. It is noted that scenarios are not meant to predict future trends, nor do they quantify the possible future outcomes, but rather can be used to explore the different possible outcomes to strategize alternatives and range of options (O’Neill et al., 2017; Pederson et al., 2021). Recently, evaluations of the RCP 8.5 scenario have raised concerns on how it explores a high-risk future that it is not a ‘business as usual’ scenario but a scenario representing the highest emissions pathway (Hausfather and Peters, 2020). When modeling with other climate change scenarios the adaptation pathways trajectories will suggest different results. Unlike adaptation, mitigation is a global-scale issue where municipalities cannot control future mitigation scenarios independently; therefore, it is difficult to determine target mitigation scenarios and expect direct adaptation. Therefore, local decision-makers must prepare for a range of mitigation scenarios and be ready to implement transformational and aggressive adaptation strategies (Chhetri et al., 2019) to deal with uncertain impacts of climate change, such as those expected under RCP 4.5 and 8.5.

2. Prioritizing adaptation options considering multi-sector impacts

In the second problem case, multi-sector risks were considered to select and prioritize of adaptation options in Seoul. The relative difference in the impact curves of the two sectors evaluated causes a unique adaptation challenge where prioritization may change over time. Conventional adaptation options and green infrastructure (GI)/ecosystem-based adaptation (EbA) options were distinguished to evaluate the co-benefits of selecting green options over conventional options (Berry et al., 2015). Implementing adaptation with co-benefits through integrated approaches can result in “win-win” situations to society beyond mitigation and adaptation and increase the cost-effectiveness of measures (Laukkonen et al., 2009; Giordano, 2012).

The multiple functions of GI deliver ecosystem services (i.e. provisioning, regulating, and cultural services) and resulting benefits to humans that encompass environmental, social, and economic values (Hansen and Pauleit, 2014). These include, for example, reduced urban heat island (UHI) effects, increased CO2 sequestration, improved water and air quality, improved social cohesion, more recreation and tourism opportunities, and increased property values, among many others (Naumann et al., 2011; Zolch et al., 2016). For example, well-managed green roofs can simultaneously contribute to adaptation by reducing stormwater runoff and UHI effects as well as mitigation by increasing carbon sequestration and reducing building energy consumption, while providing aesthetic benefits and habitats for biodiversity (Oberndorfer et al., 2007; Shaw et al., 2007). These interactions in green infrastructure was considered in our study as well as the trade-off in cost-benefit against conventional adaptation options.

Additionally, the social discount rate considering climate change uncertainty is used to evaluate the influence of economic policies on adaptation planning. Using Kang et al. (2019)'s estimation of a social discount rate (SDR) with regard to climate change uncertainty for the Korean economy, this study seeks to assess whether a social discount rate applied to green infrastructure based adaptation options affect the optimized sets of adaptation pathways and the options identified as most cost-beneficial. We assume that there is a linear effect in applying a SDR to increase the use of GI based adaptation options, which ultimately alter the outdoor thermal environment and adapt to rising heat related mortality.

Collste et al. (2017) and Mainali et al. (2018) showed that integrated approaches better highlight the synergies and trade-offs between different sectoral adaptation goals. Identifying the linkages between cross-sectoral goals can lead to stronger synergies (Mainali et al., 2018), while utilizing the identified synergies leads to systemic improvements that favor the achievement of the goals (Collste et al., 2017). It is important that studies aiming to assess the outcomes of adaptation strategies employ approaches that account for the cross-sectoral feedbacks, constraints and their differing importance within alternative socio-economic futures (Rosenzweig et al., 2017; Schellnhuber et al., 2014). However, very few models and studies incorporate all the above factors in their framework (Holman et al., 2018). Earlier studies have stressed the importance of considering the possible unintended negative impacts of adaptation actions on other sectors to optimise adaptation efficacy (Barnett and O'Neill, 2010; Juhola et al., 2016). Using these problem settings this study is conducted using the adaptation pathway model explained in detail in the next section.

IV. Methods

This study focuses on adaptation using infrastructure-based, hard adaptation strategies. The adaptation benefits are quantifiable against reduction of impacts and thus the uncertainties of future conditions remain the main question of this study. In an attempt to systematically but without prescribing the future scenarios using predefined variable parameters the exploratory modeling approach is used to model adaptation pathways. This section of the thesis outlines the architecture of the adaptation pathway model and the input values used for modeling.

The sequential aspect of adaptation pathways takes the form of stepwise planning where a decision to take action (increase, reduce or maintain adaptation) occurs at each planning period conditional to the previous period's decision. The goals and constraints at each planning period are considered independently but once sequenced the adaptation pathway over the entire planning lifetime can be evaluated as a single plan. The critical values used as triggers at action points are mostly based on logical assumptions, expert opinions, or historical data (Hamarat et al., 2014) and predefined under scenarios (Beh et al., 2015; de Ruig et al., 2019). In this study, we defined the gap between the impact and adaptation effect as the signpost to determine whether further action is needed or not.

1. Adaptation pathway model architecture

1.1. Model algorithm

Optimization approaches can be adapted to solve multi-objective problems by turning the problem into a single-objective problem or finding a set of solutions that are not dominated. A non-dominated solution results when there is no alternative solution that performs better on all objectives. There is no single solution but set of Pareto optimal solutions called the Pareto front. An effective search method for multi-objective optimization is the use of evolutionary algorithms (Hamarat et al., 2014). Evolutionary algorithms use a population of solutions where it evolves in such a way that it maintains diversity, while continually moving towards the Pareto frontier. In this way, multiple Pareto front solutions can be found in a single run of the algorithm. In this paper, we use the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) (Deb et al., 2002) as it remains the most popular multi-objective evolutionary algorithm due to its fast non-dominated sorting procedure (Ward et al., 2015; Zatarain Salazar et al., 2016), which searches for Pareto optimal solutions using non-domination ranking and crowding distance. Its efficient, elitism sorting approach allows for maintaining both diversity and convergence of solutions, especially with less-complex problem formulations with limited number of objectives as presented in this study.

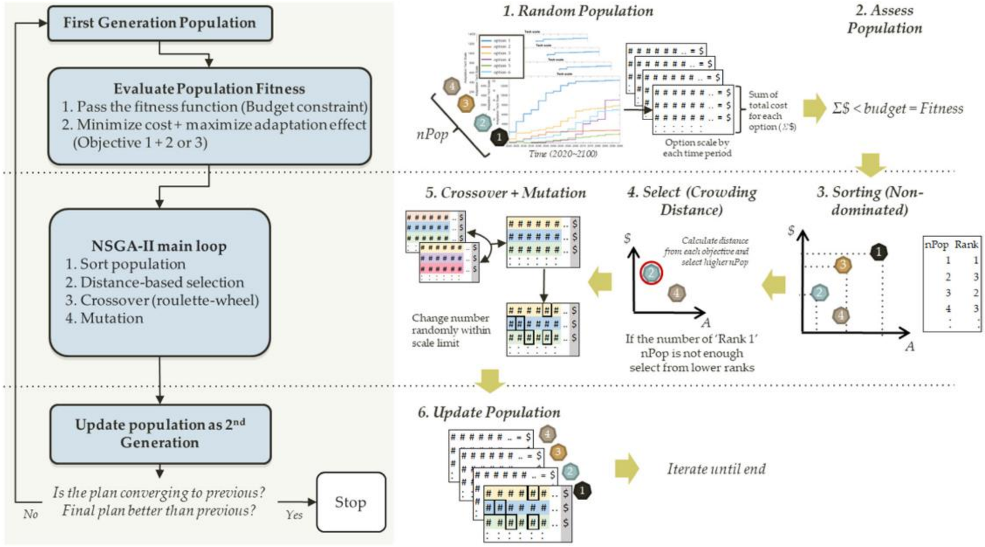

Fig. 4 Flow of optimization model (NSGA-II)

Adaptation pathways for reducing impacts from 2020~2100 were generated as 16 consecutive 5-year plans referencing Korea's current adaptation planning period. We first randomly generate nPop initial pathways (first generation population) representative of the total decision space. Each pathway is evaluated by each decision variables (objective function) in the decision space and sorted by rank. Then, by selection, crossover, and mutation – NSGA-II's 'elitism' parameters, a new set of elite nPop pathways are created (second generation). This main loop is repeated by the set number of iterations to obtain the Pareto optimal pathways.

1.2. Objective functions

Optimal adaptation pathways were evaluated based on total cost and impact reduction. In the model, these two criteria are represented as objective functions - minimize the total cost (Objective 1) and maximize adaptation based on the decision-maker’s goal (Objective 2) of each adaptation pathway. Each objective function is described below:

$$\mathit{Objective1} = \mathrm{minimize}\left\{ x_k \left[\frac{C_{i,\ k}}{(1+r)^t} + \frac{C_{r,\ k}}{(1+r)^t} + \sum_{n=1}^{t} \left(\frac{C_{a,k}}{(1+r)^t} \right) \ \right] \right\}$$

$$\mathit{Objective2} = \mathrm{minimize}\left[\sum_{n=1}^{t} (\mathit{impact}_n - \mathit{adaptation}_n) \ \right]$$

Where:

$$t = \frac{80\ \mathit{years}}{\mathit{planning\ \ period}}$$

$x = \#\ \mathit{of\ \ adaptaiton\ \ option\ \ implemented}$

$r = \mathit{discountrate}$

$C_i = \mathit{fixedcost}$

$C_a = \mathit{operating\ \ (annual)\ \ cost}$

$C_{r,} = \mathit{replacement\ \ cost}$

The cost of each pathway is calculated based on the initial and additional scales of each adaptation technology discounted by the interest rate.

1.3. Model parameters

To prevent the search from falling into a local optimum and not lose potential good solutions, the algorithm's elitism parameters were selected with repetitive pilot tests. The population size, nPop and number of iterations, which determine the efficiency of the optimization were set as 200 and 2000 using a commonly used convergence metric called the Hypervolume (Fonseca et al., 2006). The hypervolume value indicates the quality of the solutions in terms of proximity to the global optimum and diversity in coverage of solutions across the Pareto front. Various population sizes ranging from 100 to 500 plan sets and a range of iteration numbers, 500~2000 iterations were tested for efficient optimization. Premature optimized Pareto sets of solutions was found with less than 200 population sets and 1000 iteration as the hypervolume of each iteration continued to increase when these numbers increased. A population size of 200~300 and 2000+ iterations was identified as most efficient where the hypervolume value either decreased after the ~1800th iteration or remained the same after the ~1600th iteration for all scenarios.

To test for further on the reliability of the model's search for optimality, the model was run twice for all the cases of decision variable settings and the resulting Pareto of adaptation pathways were compared. In addition to the convergence test using the hypervolume value, the last 100 iterations of each Pareto of adaptation pathways were compared to one another, to find that the range of solutions had differences of less than 5% between the 1900th iteration set and 2000th iteration set. The efficiency of the model was most determined by the budget constraint, where lower budgets increased the difficulty of search for optimal adaptation pathways, increasing the search time by approximately 20% from ~300 minutes to ~360 minutes.

The non-dominated optimization of adaptation across two sectors and cost minimization may be at risk of biased optimization of one objective over another. This may be due to the different unit scale of the three objectives where the larger the unit the wider the optimization search occurs relative to the other objectives. In this study's case, the unit of the health sector was 10^2 units lower than the water sector impact-adaptation and the total cost of adaptation. Thus, scaling of the units was conducted to test whether our model was sensitive to the unit scales of objectives as shown in Fig. 5.

Scaling of the objectives did not result in much of a difference compared to the raw data optimized results. Thus, the raw values were used to portray the decision-making process where the cost of adaptation in lower in certain sectors but the prioritization is not sensitive to the price of impacts.

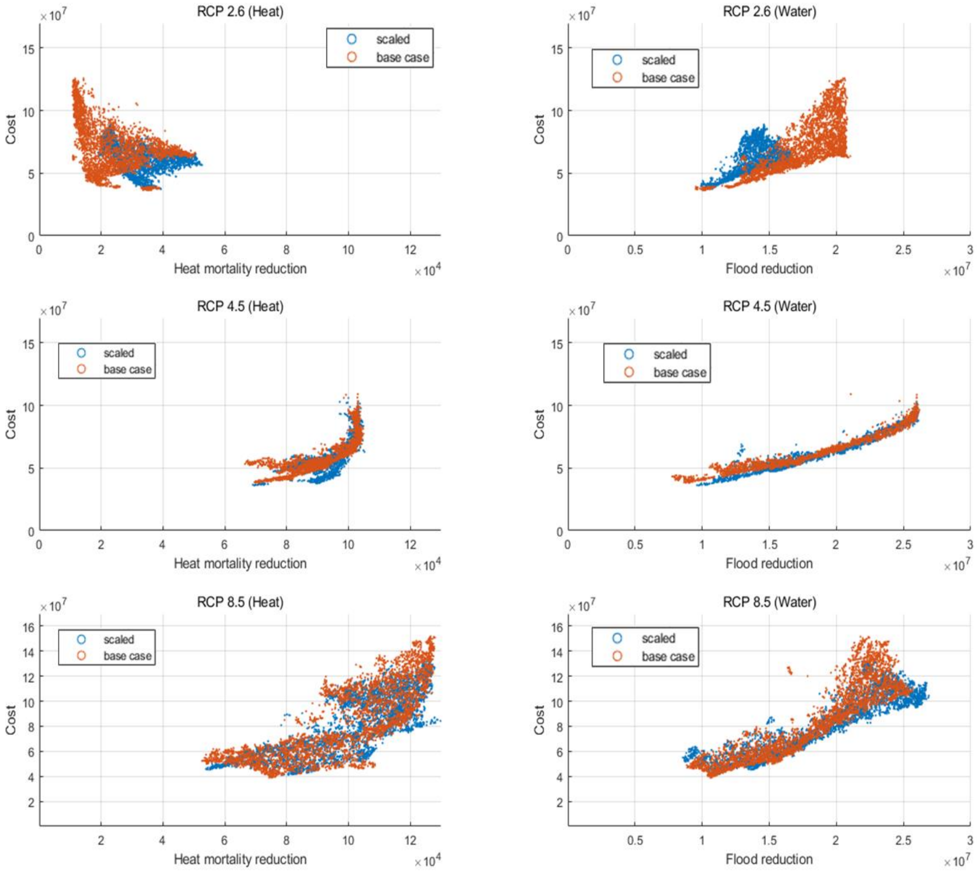

Fig. 5 Optimization result of scaled vs. raw values for each objective across RCP scenarios

Using these optimization parameters, the following section explains the results modeled to optimize adaptation pathways based on each decision variable setting as well as the reliability of the model as a tool for decision-makers.

2. Model inputs

2.1. Future impacts by sector

In the case of Seoul, heat-wave related mortality will double from 100.6 deaths per 100,000 people in 2011 to 230.4 deaths/100,000 people in 2040 due to the rapid increase in the number of people over 65 (Korea Meteorological Agency, 2018). The health impact is derived from projection models (Lee et al., 2018; Lee and Kim, 2016), which project extreme heat related mortality in Seoul according to RCP Scenario 4.5 and 8.5 up to 2100.

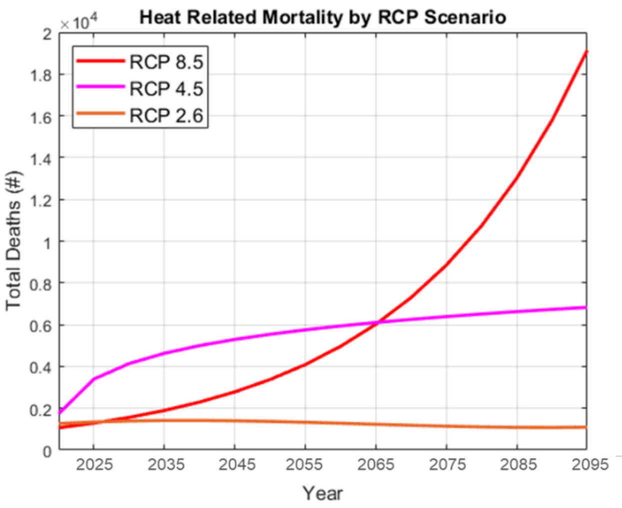

Fig. 6. Health sector impacts by RCP scenario

Annual urban flood damage was quantitatively analyzed for the next 80 years (2021–2100) using the precipitation trends according to climate change scenarios (RCP 2.6, 4.5 and 8.5) provided by the Korea Meteorological Administration and flood risk thresholds across Seoul (Kim and Kang, 2020). Past flood events, geophysical landscape (DEM), current sewer system were evaluated to quantity future annual excess runoff from rainfall (Fig. 7).

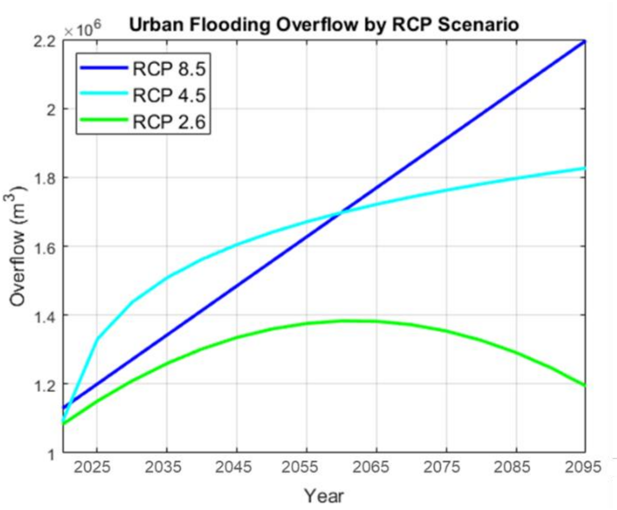

Fig. 7. Water sector impacts by RCP scenario

Future impact projections according to mitigation scenarios are used as references to guide decision-making for adaptation planning. The differences in number and trajectory (shape of impact curve) are relatively significant as they are projections and not exact predictions of future settings. The referenced projections were scaled to the Seoul region as per the referenced citation or modeled for the purposes of this study.

2.2. Selected adaptation options

In South Korea, all levels of government (national, provincial and local) are required to establish ‘climate change adaptation plans’ every 5 years (Hyun et al., 2019). Seoul, the capital city of South Korea, like other provincial and metropolitan cities, established its first implementation plan in 2013 and its second adaptation plan in 2017 to accomplish the goal of “reducing the risks due to climate change and realizing opportunities” under the vision of “building a society where people are happy and safe with climate change adaptation” (Seoul Metropolitan Government, 2017). Seoul is home to 9.73 million residents with an annual budget of approximately $30 billion. With rising concerns on the impacts of extreme heat and stormwater runoff, both Seoul and Busan city have prioritized adaptation actions for this sector. In Seoul’s adaptation implementation plan, the adaptation options in response to health impacts from heat waves include, heat wave evacuation facilities (cooling centers), cooling fog system, heat wave forecast/warning system, various green infrastructure, emergency response education and communication campaigns. etc. While the adaptation options in the first adaptation implementation plan focused on systematic, policy improvements for heat vulnerability, in the second plan, more physical, structural measures were adopted.

Heat mitigation strategies can help to select adaptation measures based on the quantifiable metrics such as air temperature reduction, radiation heat load, or human discomfort values (Park et al., 2019). In this study, the metric used to quantify adaptation effects was heat-wave related mortality numbers from direct policy measures estimated from a binomial regression analysis (Yang and Yoon, 2020) and derived from reduced mean radiant temperature, MRT with green infrastructure installments (Park et al., 2020). The first three options, planting street trees, installing green walls and greenways, reduce mortality caused by extreme heat by mitigating the heat of outdoor environment and indirectly reduce the impacts on human health. Research on the functional adaptation effects of green infrastructure have highlighted their heat reduction capabilities (Mullaney et al., 2015; Zölch et al., 2017) yet, adaptation strategies focused solely on urban greening based on current best practice are unlikely to cope with the increasing levels of urban heat risk (Kingsborough et al., 2017). So, three soft adaptation policies, establishing public cooling centers, road sprinkling, communication efforts including heat warning alarms which have been found to have statistically significant adaptation effects for the case of Seoul (Yang and Yoon, 2020) were included in this study.

Urban rainwater management in Seoul is comprehensively and systematically planned under the 'Seoul Metropolitan Government Ordinance on Rainwater Management.' The basic goals and directions for rainwater management policies as well as plans and guidelines for rainwater management to prepare efficient rainwater management facilities have been announced in 2013 with the goal of reducing annual surface outflows up to 40 percent of the average annual rainfall in Seoul. According this plan, implementation of various LID strategies have since been established according to lower-level government initiation.

The maximum number of units that each adaptation option could be implemented was set based on Seoul's current built environment conditions, such as street length, building wall areas, building space, etc. as well as future population projections and relevant long-term policies (Table 2 and 3).

Table 2. Cost and benefits of selected adaptation options for health sector

Option	1 Unit(x) /Year	Max Unit(x_t)[a]	Adaptation effect[b]	Lifetime (Year)	Initial Cost[c] ($1000)	Annual Cost[c] ($1000)	Replace Cost[c] ($1000)	Source
Street Tree	10 trees	1~20,000	$[0.02\log(t)+0.009]x_t$	80	16	0.96	9.6	Park et al. (2018; 2019)
Green Wall	10 building walls (100m^2)	1~15,000	$[0.0004(t)+0.01]$	30	19	1.71	13.3	
Greenway	100 patches (10m^2)	1~16,000	$[0.0003(t)+0.01]x_t$	5	6.5	0.19	5.85	
Cooling Center	10 new facilities	1~15,000	$[0.048(t)]x_t$	20	8.8	1.32	3.52	Yang and Yoon (2020)
Road Sprinkle	250km of sprinkle	1~8,000	$[0.003(t)]x_t$	15	7.5	0.8	6	
Heat Warning	100 campaigns	1~15,000	$[0.00004(t)+0.01]x_t$	1	2.8	-	-	

[a] x_t = number of adaptation options to be implemented at time *t* (1~80 years)
[b] Estimated reduction of heat-wave related mortality from implementing one unit of adaptation option at time *t* (Park et al., 2018; 2019; Yang and Yoon, 2020)
[c] The estimates are total present value costs, discounted using a 4% discount rate.

To consider adaptation effects and costs of each option dynamically, time and a discount rate were included in the calculations. Figure 6 and 7 shows the adaptation effect of each strategy over time according to the annual costs incurred from one unit of strategy implemented.

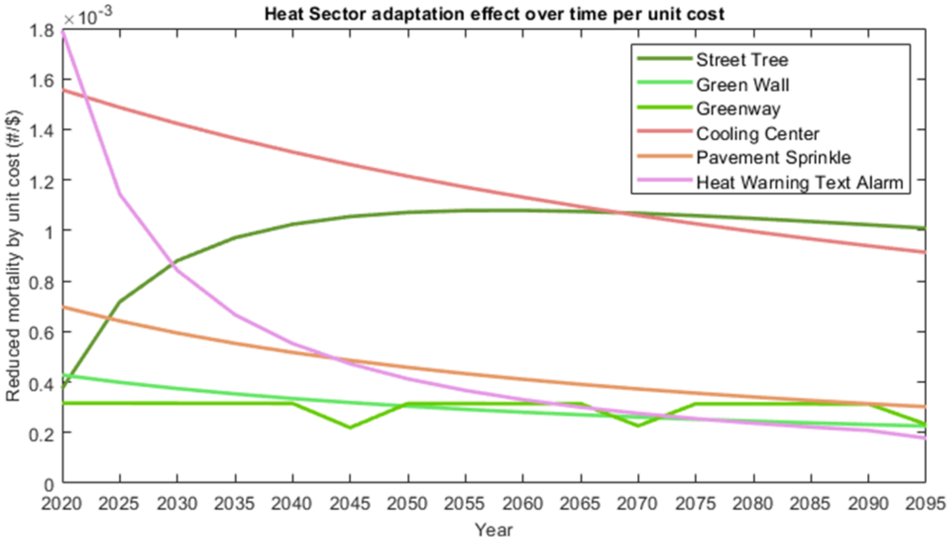

Fig. 8. Effect of health sector adaptation strategy by unit cost over time (Persons/$)

Implementing cooling centers and investing in pavement sprinkle trucks are inefficient over time with the increasing cost of upkeep of the strategy while the effect is uniform across time. Heat warning communication efforts are considered to have an educational purpose and can in fact mitigate future actions of citizens to better protect themselves from heat impacts (Casanueva et al., 2019). Green walls' effect decreases over time with growing costs while greenways, when well-kept have slightly increased effects over time. Street trees are the only adaptation strategy that has significant increasing impact reduction effects.

The contribution of GI to climate adaptation has been widely addressed in the literature for managing flood risks by reducing rainfall runoff volumes and peak flow through interception, infiltration, retention and storage of rainwater (Eckart et al., 2017; Choi et al., 2021). Permeable pavement is installed on the impervious surface to induces rainwater penetration and has been installed to more than 20% of paving in Seoul as of 2015. Street tree boxes drains rainwater via stormwater management infrastructure below the planting but serves to delay the overflow. Most street trees in Seoul serve as overflow reducing adaptation option. Greenways and green roofs are shallow runoff delaying adaptation options that also purifies stormwater. In Seoul, growing number of green roofs are being installed. Lastly, bioswales and rainwater detention tanks are designed to store rainwater from impervious areas and thus reduce runoff as the volume of the tank, swale volume size. Seoul has installed rain barrels since 2005 from no tanks to more than 400 tanks as of 2021. Efforts to encourage installation of rainwater detention tanks have been announced with household subsidy programs in addition to state funded tank installations.

Table 3. Cost and benefits of selected adaptation options for water sector

	1 unit	max unit	adaptation effect	initial cost	annual cost (% initial cost)	lifetime	replacement cost (% initial cost)
Street tree box	1 (1m3)	1 - 200,000	0.003*log*i+0.86	32	6%	60	50%
Greenway	1 m3	1 - 285,000	0.00002*i+0.92	36	19%	10	50%
Bioswale	1 m3	1 – 185,000	0.000015*i+0.94	50	15%	30	50%
Porous Pavement	10 m3	1 - 162,000	10*(-0.00618*i+1)	370.8	25%	15	65%
Rain Barrel	3 m3	1 - 225,000	3*(-0.00098*i+1)	241.1	12%	25	70%

Unit scales of each adaptation option for reducing runoff was based on recent policy goals indicating the number of installments of each option. When there was no specific reference to future policies, the trajectory of growth in installment of adaptation options from 2010 to the present was used for prediction. Adaptation effect was found from various sources including Korea’s national government survey and other literature review.

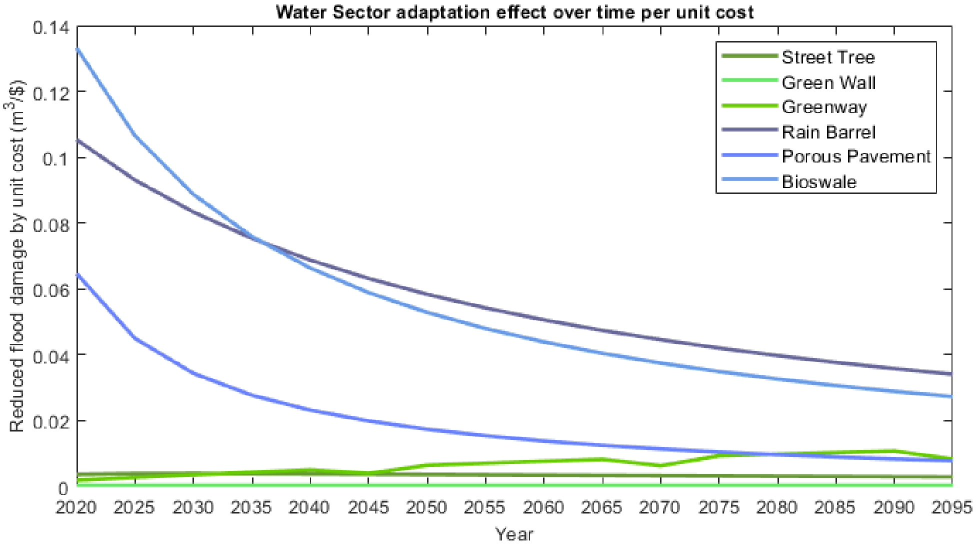

Fig. 9. Effect of water sector adaptation strategy by unit cost over time (Persons/$)

Runoff reduction is most efficient using bioswales but due to high maintenance costs, over time rain barrels are a more efficient. Porous pavement lacks in efficiency due to even higher maintenance costs while green infrastructure based options have little to no effect in reducing rainfall runoff. Greenways and trees still have minimal effect due to their sediment storage capacity.

2.3. Decision problem settings

Under IPCC’s definition of maladaptation, the optimal level of adaptation equalizes the marginal adaptation cost and the marginal adaptation benefit. In suboptimal situations, when there is too much or too little investment in adaptation, investing $1 more on adaptation results in less than or more than $1 worth of reduced residual cost of climate change (IPCC, 2014). In other words, too much or too little investment in adaptation may lead to maladaptation based on the adaptation goal. Three different decision variables were considered to model adaptation pathways: adaptation goals, budget levels and the timing of investment.

First, two different settings were used to define the type of adaptation goal. The first type of adaptation goal considers reducing the impacts as much as possible and the projected impact curve to be the minimum threshold (maximized adaptation). Mathematically, 'maximized adaptation' (Objective 2B) was represented as a minimization function transforming it into a negative.

$$Objective2_A = \mathrm{minimize}\left\{ \sqrt{\left[\sum_{n=1}^{t} (impact_n - adaptation_n)^2 \quad \right]} \right\}$$

The second type of adaptation goal considers the impact curve to be the baseline reference case where reduction efforts should stay as close as to projected impact level as possible – more adaptation is inefficient (fitted adaptation). In other words, 'fitted adaptation' (Objective 2A) is achieved when minimizing the "gap" between the impact curve and adaptation effect (sum of squares of the difference).

$$Objective2_B = \text{minimize}\left[\sum_{n=1}^{t}(impact_n - adaptation_n)\right]$$

Second, three different budget level scenarios were set, where the ‘mid-level’ budget, the baseline case, was calculated based on the budget allocated for the adaptation option most similar to the six selected options in this study. I refered to Seoul’s second adaptation implementation plan’s total adaptation budget, which was 10% of the city’s budget, where 3% of the adaptation budget was allocated to heat-related health impacts. The ‘high-level’ budget is set to $9.4 million/year, which is 20% higher than the baseline and the ‘low-level’ budget is set to $6.2 million/year, 20% lower than the baseline budget. The budget increase rate from 2020~2100 was projected based on the trend line of Seoul’s budget increase from 2004~2019.

Table 4. Future adaptation budget scenarios

	High	**Mid**	**Low**
1 year	$9.4 million	$7.8 million	$6.2 million
80 year	$748 million	$623 million	$499 million

Lastly, as explored in de Ruig et al. (2019) the effects of delayed investments in adaptation can show the urgency of adaptation. The results of de Ruig et al. (2019) found mixed results in how delayed investments affect the relative Net Present Value (NPV) for different adaptation strategies. Economic efficiencies may be achieved at different timings across the adaptation pathways or not achieved at all. I explored whether adaptation across the adaptation pathway could achieved despite a delay of 10 years, 20 years of no action.

Previous studies on adaptation pathways consider the adaptation of one sector with large-scale, structural technologies. However, recent climate change adaptation studies have shown that multi-layer vegetation types and spaces, including green infrastructure and large trees, provide synergistic functional adaptation effects (Mullaney et al., 2015; Zölch et al., 2016). This study thus derives the optimal adaptation pathway across sectors to maximize the total adaptation effect using 3 ecosystem-based adaptation (EbA) technologies and 6 traditional options. Two scenarios, one with only traditional adaptation options and second, both EbA and traditional options were considered to evaluate the cost-benefit across an 80-year timespan. Further, the use of green infrastructure (ecosystem-based adaptation) to reduce the impacts of two urban impacts from climate change are investigated. In a post-Paris Agreement world, where global warming has been limited to 1.5 or 2℃, adaptation is still needed to address the impacts of climate change. Thus, the RCP scenarios 2.6 and 4.5 are explored extensively according to two scenario variables – social discount rate for green infrastructure and the inclusion or exclusion of green infrastructure options.

V. Results

1. Cost-benefit of adaptation based on goal settings

The results show that there is an efficient coupling of goal and budget setting within the wide range of adaptation pathways that are dependent on the goals and constraints set by the decision-maker. As suggested by Dessai and Hulme (2007), de Bruin et al. (2009b) and Hof et al. (2009) it is important to holistically consider the cost-benefit of adaptation options when planning for climate adaptation. Larger investments in adaptation does not necessarily lead to greater adaptation as we find that higher budgets are not efficient in searching for adaptation plans that aim to reduce climate impacts as close to the projected numbers as possible. Therefore, setting an appropriate budget level according to the adaptation goal should be prerequisite in planning for climate adaptation.

1.1. Optimization results according to the adaptation goal setting

Figure 8 shows the model's final 10 iterations (2000 unique adaptation pathways' total cost and adaptation, plotted and represented by an asterisk) of Pareto optimal sets for each scenario of varied decision variable settings indicated by different colors. The Pareto sets with red hues are the results of maximized adaptation while the blue hued sets are optimized as fitted adaptation, which aims to adapt as close to the heat-related mortality impact numbers as possible. Though both objectives responded sensitively to changes in budget level, the degree of sensitivity and the response itself showed very different trends especially when comparing the cost-benefits of solutions. Maximized adaptation found a more diverse range of adaptation pathways across the x-axis (total adaptation #) and y-axis (total cost) in comparison to fitted adaptation solutions. Lower budgets limit optimization of maximized adaptation to similar solutions (dotted circle) while higher budgets did not change the solutions of fitted adaptation as much as for maximized adaptation (dashed circle).

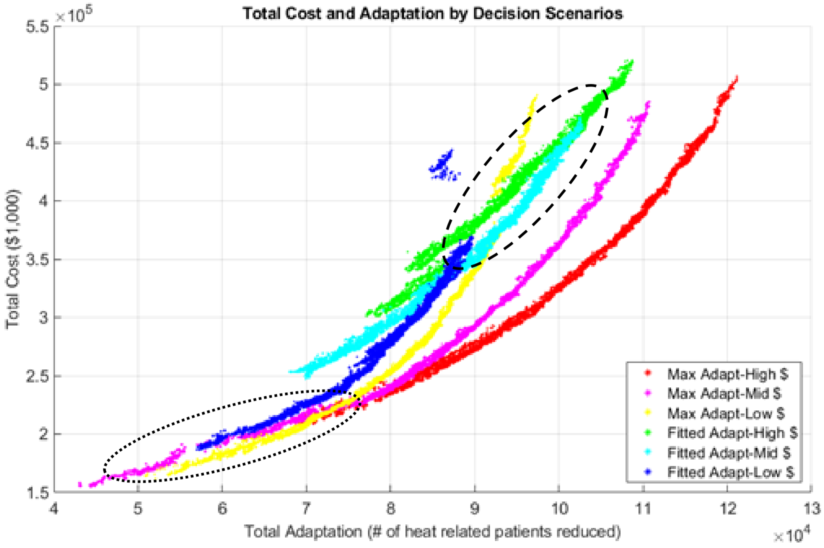

Fig. 10 Optimized pareto of adaptation pathways by goal setting and budget level

Table 5 details the median, minimum and maximum values for total heat-related mortality reduced and total cost of an adaptation pathway over 80 years amongst the set of Pareto solutions under each decision variable setting. For maximized adaptation, more adaptation is achieved with increased budgets, where the median number of heat-related mortality saved with a high adaptation budget is 102,483 people while under low budget 81,763 people are saved. Yet, the cost of adaptation linearly increases with the number of lives saved so the median cost to save 1 person is similar ($3,245~$3,326/1 person) across budget scenarios, meaning the efficiency of adaptation pathways is maintained at all budget levels. As shown in Figure 10, however, the maximum cost to save 1 person within each Pareto set is less efficient with low adaptation budgets, which indicates that tighter budget constraints limit the search for more efficient adaptation pathways when aiming for the greatest adaptation effect.

Table 5 Total adaptation effects and costs of adaptation pathways according to budget level and adaptation goal settings

Decision Variables		**Heat Related Mortality Reduced (# of persons)**			**Total Cost ($1,000)**			**Cost to Save 1 Person ($)**		
Goal Setting	Budget	Median	Min.	Max.	Median	Min.	Max.	Median	Min.	Max.
Maximized	High	102,483	69,217	121,116	340,883	208,797	504,710	3,326	3,017	4,167
	Mid	89,533	43,018	110,755	290,578	155,678	484,710	3,245	3,619	4,376
	Low	81,763	50,861	97,431	267,983	164,011	491,295	3,278	3,225	5,042
Fitted to Impact	High	94,357	77,165	108,758	408,990	301,865	518,635	4,334	3,912	4,769
	Mid	89,477	68,091	102,881	349,491	253,687	462,486	3,906	3,726	4,495
	Low	78,273	56,979	89,757	275,809	186,601	368,482	3,524	3,275	4,105

Compared to maximized adaptation, fitted adaptation found less efficient median and minimum solutions across all budget scenarios. For the maximum value solutions, the opposite was true, where fitted adaptation found more efficient adaptation pathways as the budget decreased though the absolute number of heat related mortality saved was smaller. An explanation to why fitting adaptation at lower budgets lead to cost-efficient adaptation maybe that the optimization search is more controlled with a smaller range of solutions available and thus strategic implementation of limited adaptation options at each planning period. In sum, to find cost-efficient adaptation pathways it is best to couple the constraint and objective to lower inefficient searches of sub-optimal adaptation plans. For example, a higher-budget constraint is best applicable for maximized adaptation while lower-budget constraints allow for efficient fitted adaptation plans.

1.2. Decision-maker preference effects on adaptation over time

Fig. 11 shows the level of adaptation achieved by the pathways against the impact across the 80-year planning period under three different budget levels for both objectives (shown as different shadings). The dotted lines indicate the median valued adaptation pathways while the shaded area illustrates the range of pathways from the last 10 iterations. When the adaptation pathway is drawn above the ‘0’ line, this indicates that more adaptation is attained while a positive and negative value of 0.5 means that that more or less than 50% of the impact is adapted or not adapted. As evidenced in Fig. 11, when adaptation is maximized more impact reduction can be achieved. Increased budget levels increase the level of adaptation, but the effect is minor for fitted adaptation. Meanwhile for maximized adaptation, adaptation increases by 20% at its peak in 2040 with an increase in budget level.

In the first ten years from 2020~2030 full adaptation is difficult to achieve due to the limited budget. For all adaptation goal setting and budget level, full adaptation becomes difficult to achieve after 2065. This may be explained by the limitation of advanced technology and scale of current adaptation options and given geographic, socio-political conditions.

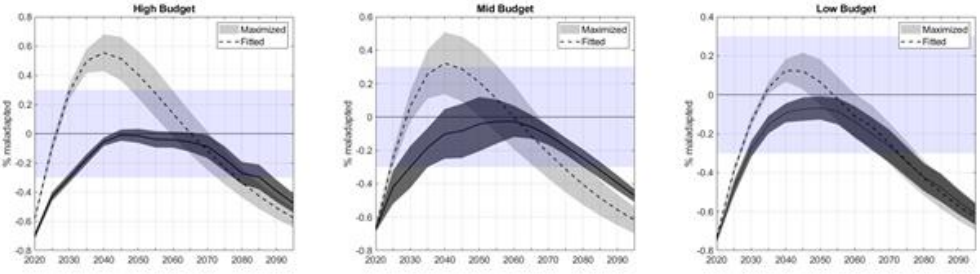

Fig. 11 Budget effects on adaptation by goal under RCP 8.5

In both goal settings, the effect of delayed investments in adaptation options critically reduced adaptation equally. Sensitivity to delayed investment is greater than the effect of budget level and adaptation goal setting as the optimal range of pathways overlap despite different search settings (Fig. 12). With a 10-year delay in investing in adaptation options full adaptation is possible for a short 15 years between 2045 and 2060, while for a 20-year delay, full adaptation is impossible for all scenarios. If a decision-maker aims for maximized adaptation, immediate action is a prerequisite before setting other decision variables.

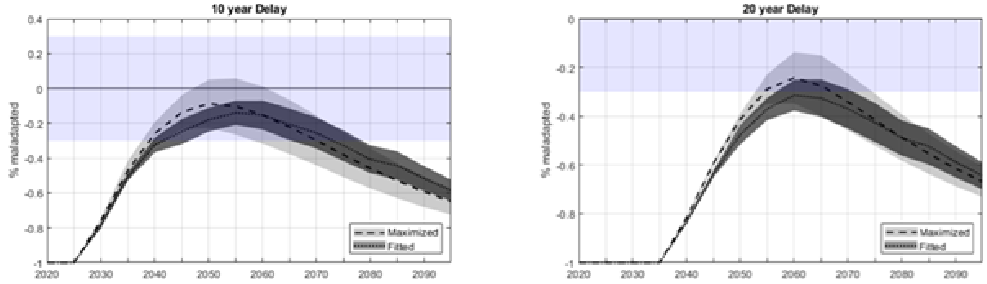

Fig. 12 Adaptation results with delayed investments under RCP 8.5

1.3. Selecting adaptation pathways from modeled results

The above results described the trends of how the Pareto optimal set of adaptation pathways were different based on the settings of decision variables. In this section, we explain how individual adaptation pathways can be explored and drawn according to decision-maker’s preferences. Because many Pareto optimal adaptation pathways are not user-friendly information that can assist the decision-making process, it is necessary to reduce the number of alternatives given to decision-makers.

2. Prioritizing adaptation options considering multi-sector impacts

The cost-benefit of each adaptation pathway was used as the metric for selecting and prioritizing which adaptation plan alternative to select. In many previous studies, multi-criteria analysis (MCA), a multi-step method using already existing assessments or data and a scoring system with given weights (determined by experts) are normalized to rank and prioritize the alternatives. The benefit of using the adaptation pathway model with searches for alternatives using a non-dominated sorting algorithm for multi-objectives is that pathway alternatives are searched in a Pareto. This means that adaptation pathways that rank high as 'best solutions' have naturally prioritized one objective (sector) over another and vice versa. In the case of this application, three objectives – cost reduction, health sector and water sector adaptation maximization, were evaluated.

The main goal of this application was to evaluate the benefits, especially co-benefits, if any, of green infrastructure based adaptation options across two sectors. According to the identified benefit of green infrastructure, analysis on whether the 'best' adaptation pathways were different when one sector was prioritized over the other. An additional cost incentive condition, parametrized as a social discount rate, was applied to green infrastructure adaptation options. The results in the following section show the optimization pattern in search for optimal adaptation pathways under two RCP scenarios (2.6 and 4.5), with and without green infrastructure and social discount rate (standard interest rate = 4.5%, social discount rate = 3.5%, see Methods section for detailed explanation of discount rate settings).

Similar to the previous application study, a search of 1,000 iterations with a population set of 200 was conducted for each condition variable case.

2.1. Optimization results according to RCP scenarios and multi-sector objectives

The optimized adaptation pathways, determined by the convergence values achieved were after the 500th iteration. The tradeoff between the health and water sector was similar for RCP 2.6 and 4.5 as show in Fig. 13, as evidenced from the dispersal of each dot, indicating the total adaptation and cost of the adaptation pathway across 80 years. The cost difference in the searched adaptation pathways two sectors is not uniform across RCP scenarios and discount rate values. The effect of lower discount rate is uniform across different scenarios while the effect of green infrastructure is different according to the RCP scenarios.

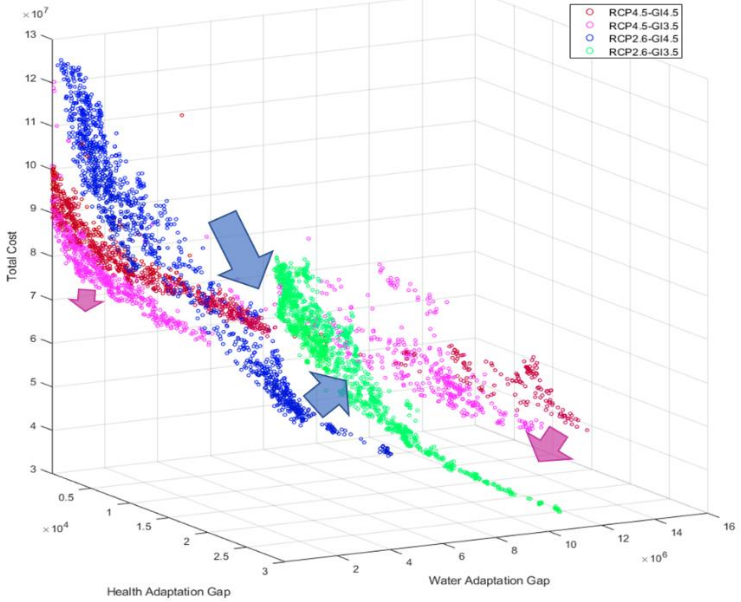

Fig. 13 Pareto optimized sets of adaptation pathways according to RCP Scenario and discount rate

The effect of a social discount rate across the pareto optimal set is different under the two RCP scenarios. Under RCP 2.6, a social discount rate significantly reduces the optimization to lower costs while the range of water sector adaptation solutions is limited. Under RCP 4.5, there was not a significant difference as compared to the difference found for RCP 2.6 adaptation pathways. As the pink arrows show a slight decrease in cost and increase in increased adaptation in the water sector was observed.

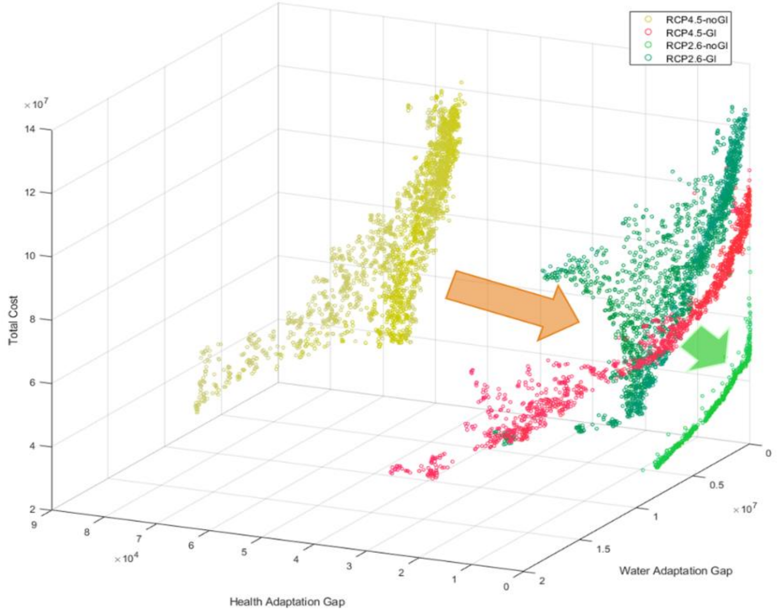

Fig. 14 Pareto optimized sets of adaptation pathways according to RCP Scenario and inclusion/exclusion of GI options

Fig. 14 shows the effect of inclusion and exclusion of green infrastructure under the two RCP scenarios. Exclusion of green infrastructure results in a contrasting change pattern for the two RCP scenarios. A much narrower range of pathway results were optimized with the inclusion of GI for RCP 4.5 while the exclusion of GI under RCP 2.6. This can be explained according to the much lower impact curve for RCP 2.6 where GI results in excess adaptation, while for RCP 4.5, GI is necessary for better adaptation.

2.2. Green infrastructure effects on adaptation over time

Adaptation for future overflow impacts is possible under RCP 2.6 and 4.5 with the appropriate technologies implemented. The range in reduced overflow is different across scenarios where the effect of green infrastructure is in fact negative. This is somewhat counterintuitive considering the effect of green infrastructure in reducing overflow. Yet, the results may be explained by the reduced amount of money available to reduce overflow with more cost-efficient conventional technologies. The relatively lower cost-efficient green infrastructures are a cost burden in the case of the water sector.

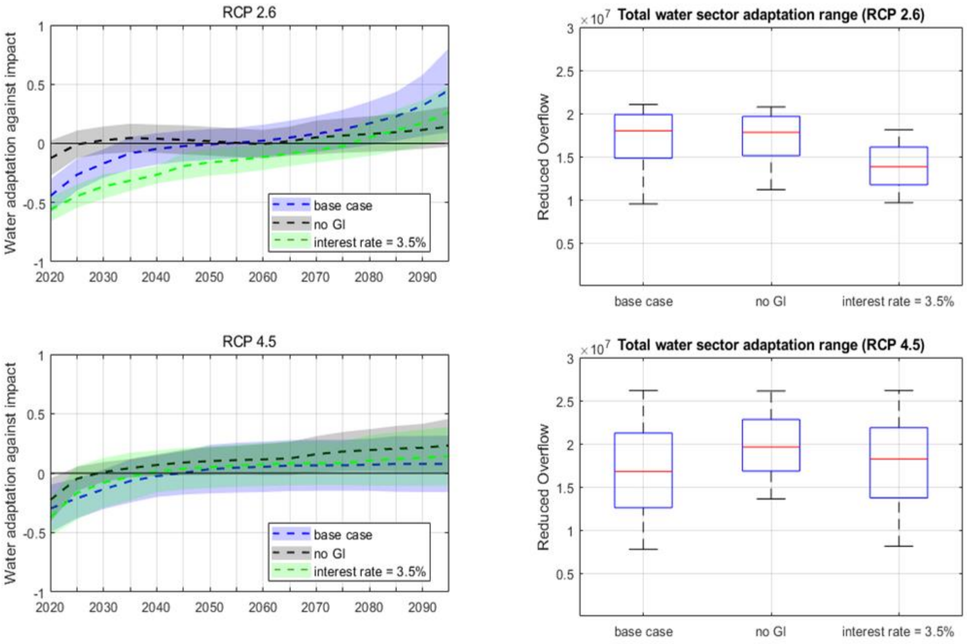

Fig. 15 Range of water sector adaptation across time according to scenarios

In contrast, for the health sector, adaptation is impossible without green infrastructure. The influence of microclimate heat reducing green infrastructure is needed in the long term as the conventional technologies to reduce heat mortality are not as effective. This may indicate the need to develop more cost-efficient technologies in reducing heat mortality or reducing the cost of green infrastructure to balance the adaptation effects of the two sectors. In the case of RCP 2.6, however the addition of green infrastructure results in over-adaptation after 2050 as these technologies' effect increase over time.

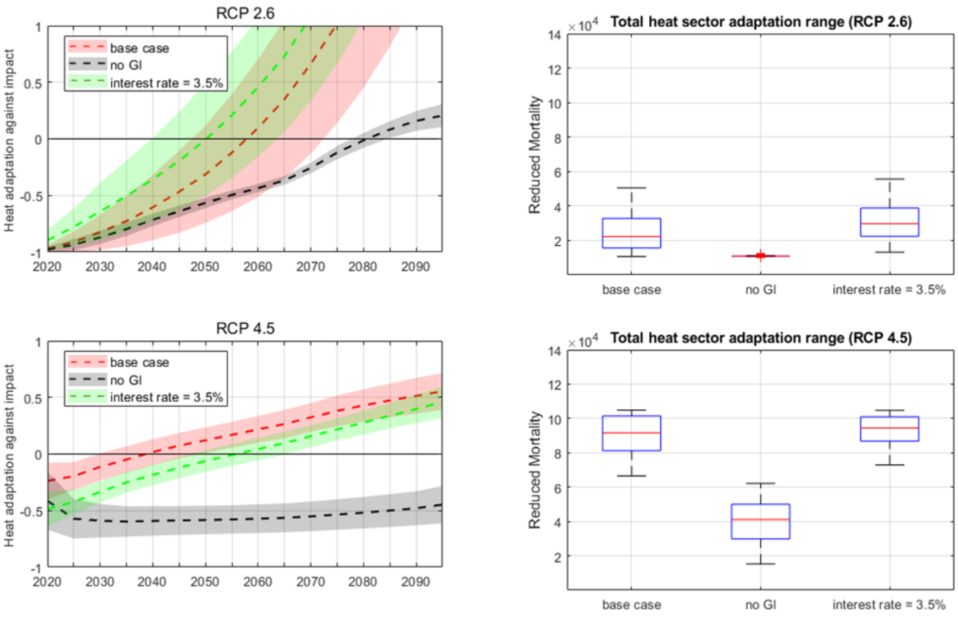

Fig. 16 Range of health sector adaptation across time according to scenarios

The addition of a social discount rate to green infrastructure resulted in opposing results under the two climate scenarios – under RCP 4.5, adaptation pathways with lower level of adaptation were identified as optimal while under RCP 2.6, greater adaptation was achieved. A holistic analysis of the impact reduction by sector and cost results may better explain the results as shown in Fig. 17.

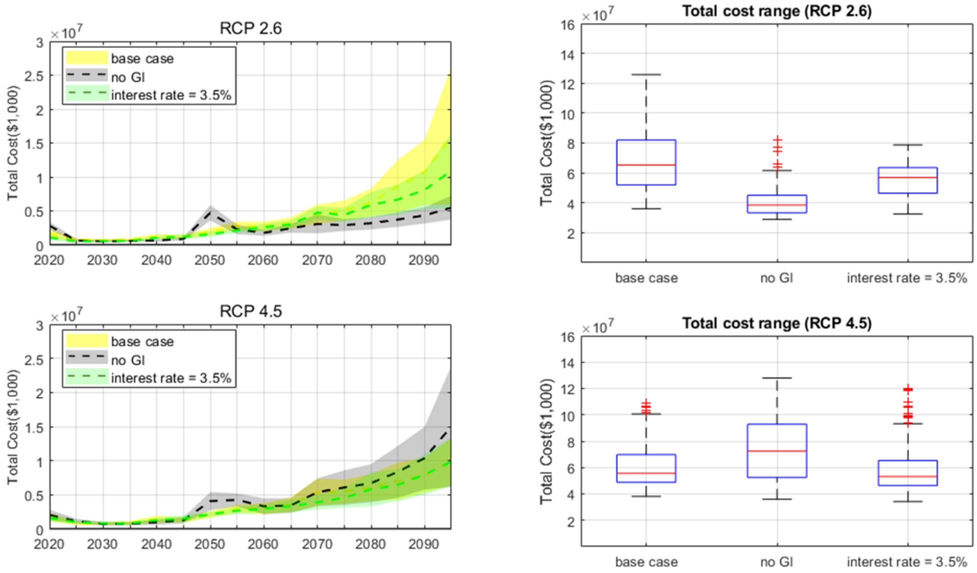

Fig. 17 Range of adaptation cost across time according to scenarios

The cost of adaptation is lower for RCP 2.6 where the cost of green infrastructure is a burden because of the relatively lower level of impact in the health sector resulting in over-adaptation. Under RCP 4.5, the cost of adaptation without green infrastructure is much higher due to the limitation of adaptation without green infrastructure. This result indicates a similar conclusion from the previous case where an efficient coupling of adaptation with impact is needed. The social discount rate did not lower the total cost of adaptation rather changed the level of adaptation achieved for both sectors.

2.3. Optimized adaptation options according to sector prioritization

The Pareto optimal sets of adaptation pathways were significantly different according to the prioritized sector and cost considerations. Such results indicate the challenges in identifying, prioritizing, and implementing adaptation plans when little guidance and information on simulations of the future are provided to establish appropriate measures for tackling adaptation. Because the adaptation model searches for cost efficient solutions, the identified 'optimal' solutions do not all achieve full adaptation. This is especially true for RCP 2.6 cases and especially when the health sector is prioritized. This can be explained by the excessive scale and effect of green infrastructure in reducing health impacts. This is not to say that non-green infrastructure solutions should be prioritized over green infrastructure since RCP 2.6 is a climate scenario with extreme mitigation efforts. Yet this results suggests that adaptation solutions depend vastly on the problem definition.

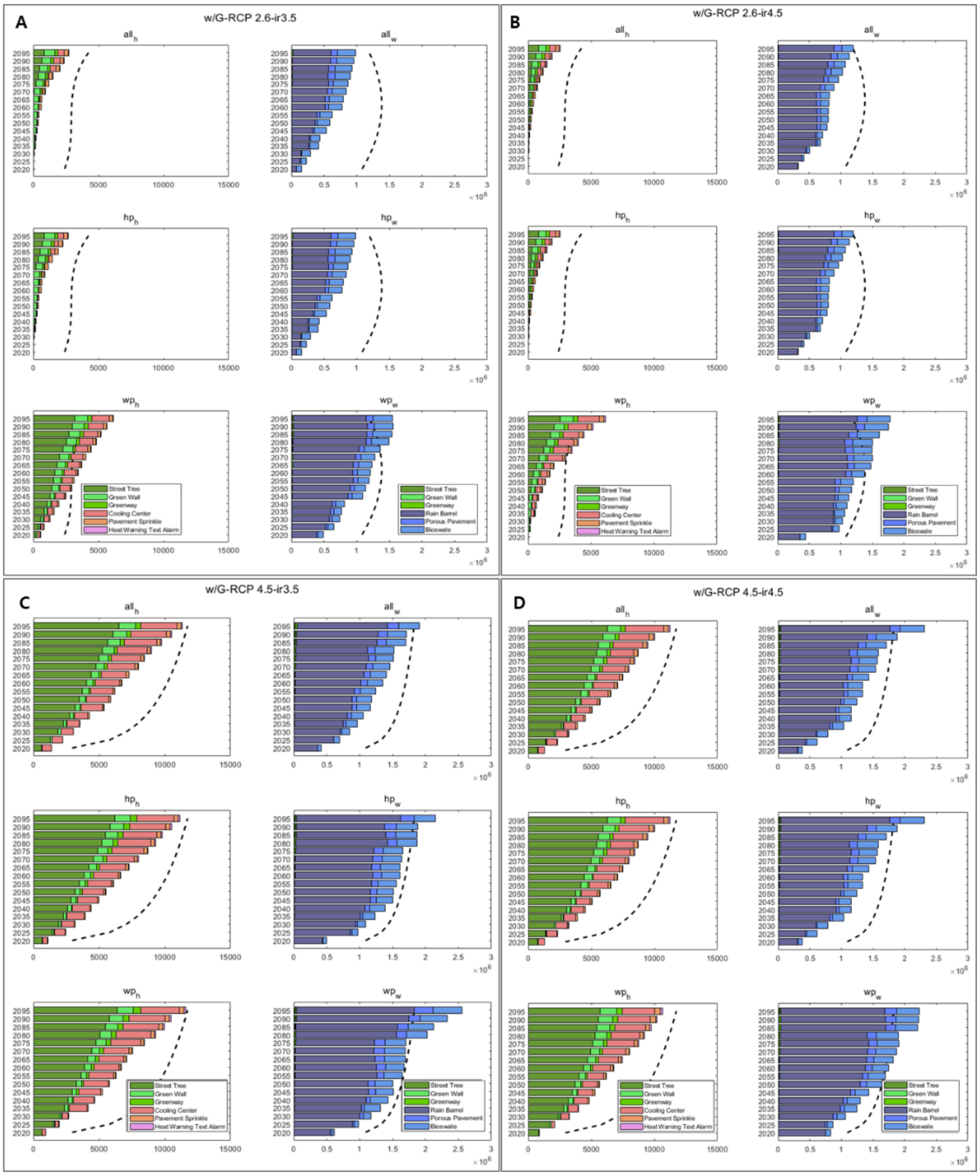

Fig. 18 Adaptation effect with no-SDR vs. SDR according to prioritized sector.

The effect of a social discount rate can be more clearly seen in Fig. 18. The dotted lines indicate the impact as a reference to how much adaptation is being achieved.

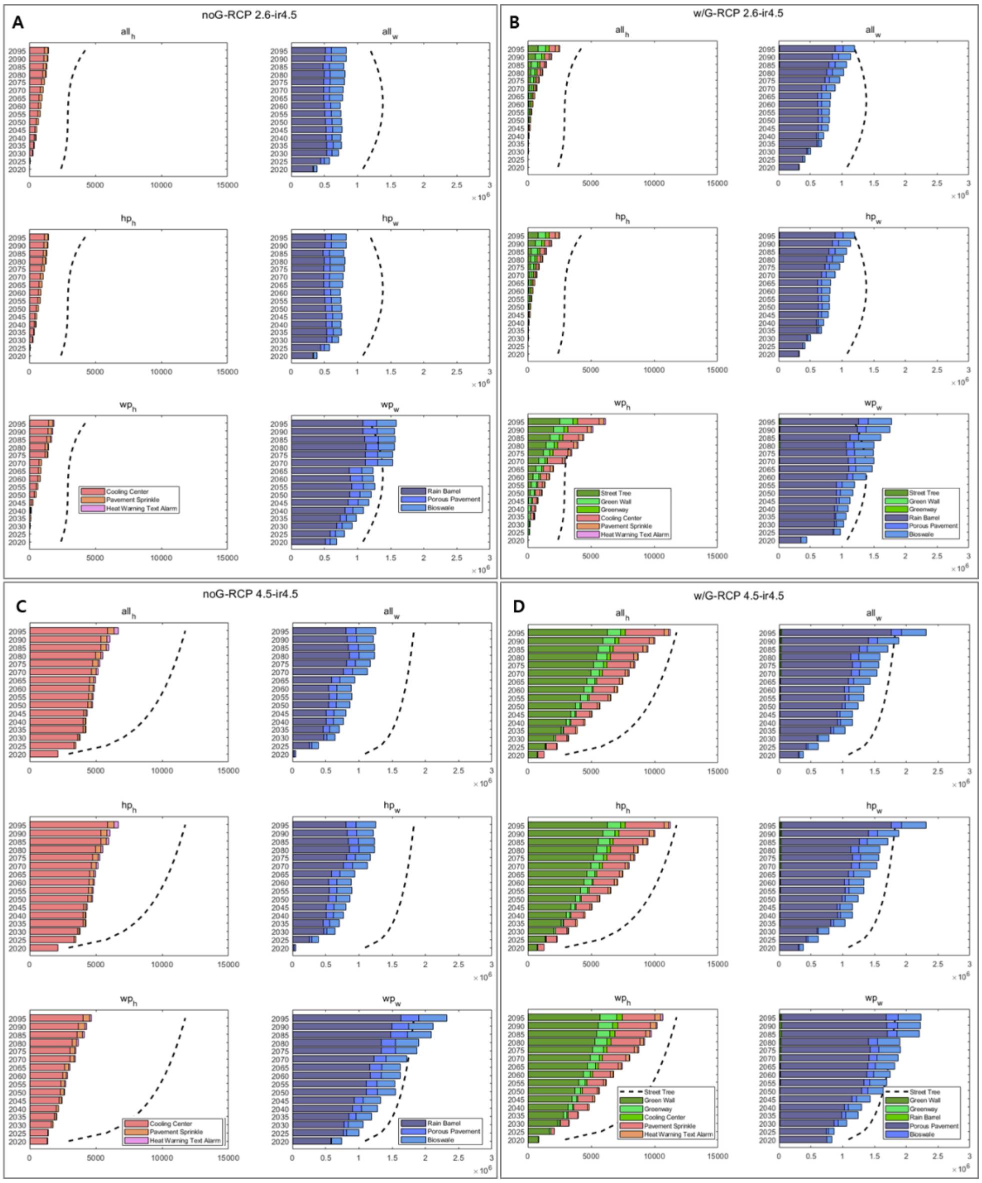

Fig. 19 Adaptation effect with GI vs. no-GI technologies according to prioritized sector

When both sectors are prioritized, adaptation is similar to heat sector prioritization. However, when the water sector is prioritized adaptation of the health sector also increases in the case of RCP 2.6. The cost-benefit of adaptation must be relatively considered as the cost of water sector prioritization is more expensive in all scenarios.

Table 6. Total adaptation effects and marginal costs of adaptation pathways according to prioritized sector and scenario cases under RCP 2.6

A) Heat mortality (total impact: 49,000ppl)

	Health Prioritized		**Water Prioritized**	
	% Adapted	Cost per unit adapted	% Adapted	Cost per unit adapted
Base Case	22.1~22.3%	$4,936~$5,589	71.1~101%	$1,392~$1,906
Green IR = 3.5%	26.9~28.9%	$4,126~$7,750	106.3~108.2%	$1,140~$1,616
No-GI	26.3~26.4%	$1,573~$,2716	25.8%	$2,397

B) Rainfall runoff (total impact: 20,600,000 m^3)

	Health Prioritized		**Water Prioritized**	
	% Adapted	Cost per unit adapted	% Adapted	Cost per unit adapted
Base Case	62.8~93.9%	$3.1~$4.7	100%	$3.02~$3.36
Green IR = 3.5%	50~50.3%	$5.54~$10.6	86.6~87.7%	$3.4~$4.67
No-GI	57.5~88.5%	$1.72~$1.93	96.6%	$2

Table 6 shows the difference in numbers the visualized differences explained for Fig. 18 and 19. Greater adaptation was achieved when water sector prioritized adaptation pathways for both sectors perhaps as a result of lesser consideration of cost reduction optimization. In the case of heat sector optimization, where GI was costly and the adaptation need for the health sector lower than the water sector, cost minimized solutions were suggested as optimal adaptation pathways.

Table 7. Total adaptation effects and costs of adaptation pathways according to prioritized sector and scenario cases under RCP 4.5

A) Heat mortality (total impact: 149,000ppl)

	Health Prioritized		**Water Prioritized**	
	% Adapted	Cost per unit adapted	% Adapted	Cost per unit adapted
Base Case	69%	\$472~\$778	66.6~69.1%	\$879~\$1,240
Green IR = 3.5%	69%	\$1,059	68.3~69%	\$840~\$1,013
No-GI	49.58~51.3%	\$497~\$533	30.9~31.05%	\$1,079~\$1,084

B) Rainfall runoff (total impact: 25,990,000m^3)

	Health Prioritized		**Water Prioritized**	
	% Adapted	Cost per unit adapted	% Adapted	Cost per unit adapted
Base Case	81.1~100%	\$1.87~\$4.2	100%	\$3.49~\$4.9
Green IR = 3.5%	33~92.6%	\$4.53~\$11	100%	\$3.32~\$3.98
No-GI	54.6~59%	\$2.57~\$2.68	96~96.1%	\$2~\$2.01

Table 7 shows that greater adaptation was achieved in comparison to RCP 2.6, while water sector prioritized adaptation pathways similarly adapted more for both sectors. Prioritization of different sectors with optimizing for cost reduction identified the need to consider multiple dimensions in planning for adaptation and proves the benefits of using exploratory modeling as a base for clearer decision-making under uncertainty.

VI. Discussion

This study evaluated and used the adaptation effects of current technologies despite projecting the adaptation effects onto future climate change impact projection scenarios. Setting the adaptation problem with different RCP scenario, the adaptation pathways found in this study present relatively ambitious actions so as to not face the irrecoverable costs and damages of the future. Recently, evaluations of the RCP scenarios have raised concerns on how it explores a high-risk future (RCP 8.5) that it is not a ‘business as usual’ scenario but a scenario representing the highest emissions pathway (Hausfather and Peters, 2020). When modeling with other climate change scenarios the adaptation pathways trajectories suggest different results. This section discusses the study result implications, limitations to the uncertainties of the model, input values and the result uncertainties as well as a synthesis of the findings and suggestions for further studies.

1. Dependency and limitations on adaptation according to future scenarios

In our study, the adaptation options identified as the most optimal – a greater number of the option were suggested to be implemented, were those with increasing effects. For all scenarios, street trees were implemented to maximum scale while the number of other adaptation options to be implemented was dependent on the budget level and adaptation goal setting. The benefits of ecosystem-based strategies can be largely categorized into two – they grow and therefore increase their adaptation effect overtime and their unit installments are much smaller in scale and cost than traditional infrastructure based adaptation. These benefits can be realized directly (in terms of cost) as ecosystem based adaptation serve as buffers to delay and reduce the investment of grey infrastructure based strategies. Without ecosystem-based strategies it is becomes a burden to adapt to exponentially increasing climate impacts due to high-cost, inflexible adaptation strategies (Nay et al., 2014; Mullaney et al., 2015)

The portfolio of eight adaptation options considered in our study limits the discussion of our finding as they are not representative of future trajectories, as it assumes no technology development, nor is it holistic of current adaptation options that reduce heat-related heat mortality. However, the finding that full adaptation cannot be achieved after 2065 in all scenarios is indicative of the need to include more and ambitious adaptation options. To introduce new adaptation options, validation of the effects of new technologies should always supplement the research and development.

Identifying and making inventories of adaptation strategies is also important for wider use of various adaptation options as the field is still in its developing stage (de Bruin et al., 2009a; Beh et al., 2015; Williams et al., 2020).

The difficulty in using quantitative performance measures for adaptation effectiveness evaluation is not straightforward (Quinn et al., 2017). Decision-makers can benefit greatly from simulation tools that allows them to explore and visualize the different outcomes from different inputs based on their decisions (Woodruff et al., 2013; Williams et al., 2020). Despite the increasing accuracy and reliability of climate information and models, such tools have not lead to better communication, suggesting that there is a gap between the climate information produced by scientists and the high quality climate services that are actually required. With climate services, climate information for decision-making is provided and users' needs must be satisfied, and for this, convenient and regional information must be jointly produced and supplied. Finally, climate information services can include guidelines for the use of science-based climate information (Bessembinder et al., 2019; Williams et al., 2020).

With technological advances in science, this gap has existed from the beginning of the concept of climate services, but is more closely related to how science is communicated and used (Bremer et al., 2019). Until now, most of them have focused on supplying expert knowledge from the perspective of information providers (van Stigt et al, 2015). Therefore, understanding how actual users (decision-makers) perceive this information, how information is used in practice or to what extent user needs need to be reflected must be considered for wider applicability of adaptation planning support models.

The challenges in adaptation planning are more apparent for local scale adaptation, where local impact assessments face greater uncertainty stemming from simulated, down-scaled future climate change scenarios. The present study has the limitation of high uncertainty in projections for Seoul’s extreme heat-related mortality, rainfall overflow and evaluations of each adaptation option’s effects. Further research is needed for greater reliability in applying the methodology introduced in this study.

2. Avoiding maladaptation through economical decision-making

As suggested by Dessai and Hulme (2007), de Bruin et al. (2009b) and Hof et al. (2009) it is important to holistically consider the cost-benefit of adaptation options when planning for climate adaptation. Thus this study considered the total impact reduction and costs of implementation equally when optimizing for adaptation pathways. Based on our study's results the two economic considerations, delayed investments and level of budgets, determined the degree of adaptation achieved. Larger investments in adaptation does not necessarily lead to greater adaptation as we find that higher budgets are not efficient in searching for adaptation plans that aim to reduce climate impacts as close to the projected numbers as possible. Therefore, setting an appropriate budget level according to the adaptation goal should be prerequisite in planning for climate adaptation.

Delayed investments greatly limit the level of achievable adaptation when optimized against the cost-benefit of investing in adaptation options. Such results are in line with de Ruig et al. (2019) where economic efficiency decreases when an investment is not fully utilized across time. For efficient and effective adaptation, immediate action is required. The lack of efficiency in delayed investment and unbalanced coupling of budget constraint and adaptation goal identified in our model results is relevant to the concerns of 'maladaption' (IPCC, 2014). The definition of maladaptation includes both inadequate and inefficient adaptation due to the lack of systematic assessment and short-term perspectives. Maladaptation warns against actions that set path dependencies that cannot be easily corrected and actions that preclude alternative approaches. With future uncertainties, avoiding maladaptation is difficult unless a flexible planning approach is taken to incorporate future changes. Applying an adaptation pathways approach allows for adjustable planning as adaptation options can be increased or decreased sequentially over time.

Differences in results based on the goal setting also demonstrate the repercussions of policy implementation depending on how science is translated, meaning explicit efforts to apply user-driven approaches to utilize and act on climate science to practical applications. Future climate impact numbers, such as heat related mortality count, can be used differently to deliberate action according to the perceived urgency. If impact values are understood as threshold values, these values can be used to set a definite goal for adaptation, while impact numbers used as references can be used as a general baseline. In the case of our study heat-related mortality numbers, when used as threshold values would translate into setting the adaptation goal to maximize adaptation since the objective is not avoid all deaths from climate impacts. When the projected mortality numbers are used as a reference where decision-makers may want to prioritize the cost-benefits of their plan, the adaptation goal would be to plan as close to the impact curve to avoid inefficiency. Yet, for climate adaptation the uncertainties in future impact projections according to the RCP scenarios are not nuanced enough to set definite goals. The ability to decipher and select among the simulation results is not intuitive and requires a learning-by-doing process. Therefore, flexible and adjustable planning approaches are a suitable best-practice for decision-making and implementation of adaptation plans according to the available information.

3. Developing the adaptation pathway model as a climate service

Use and understanding of science based climate information is a prerequisite and inevitable to supporting decision-making when establishing adaptation plans despite their complexity (van den Hurk et al., 2018). Resources for guidance of climate information is steadily increasing, but the understanding of decision makers and implementation of adaptation measures is still insufficient (Dilling and Lemos, 2011, Olazabal et al., 2019, Webber, 2019). In particular, it was found that there is a lack of knowledge about integrating climate forecasting with decision making and policy planning (Hewitt et al., 2013). Visscher et al. (2020)'s framework for classifying climate services according to the complexity of climate information and local conditions considered by the user, assists identifying the type of useable data. Since it is difficult for users with low background knowledge about climate information to find and compare necessary climate services, when science-based climate information is provided, guidance and education supplements are suggested.

The model developed in this study aims to directly assist the long-term decision making process for adaptation planning stakeholders in selecting which, when, how much of adaptation options to achieve their adaptation goal under different future climate scenarios and socio-economic conditions.

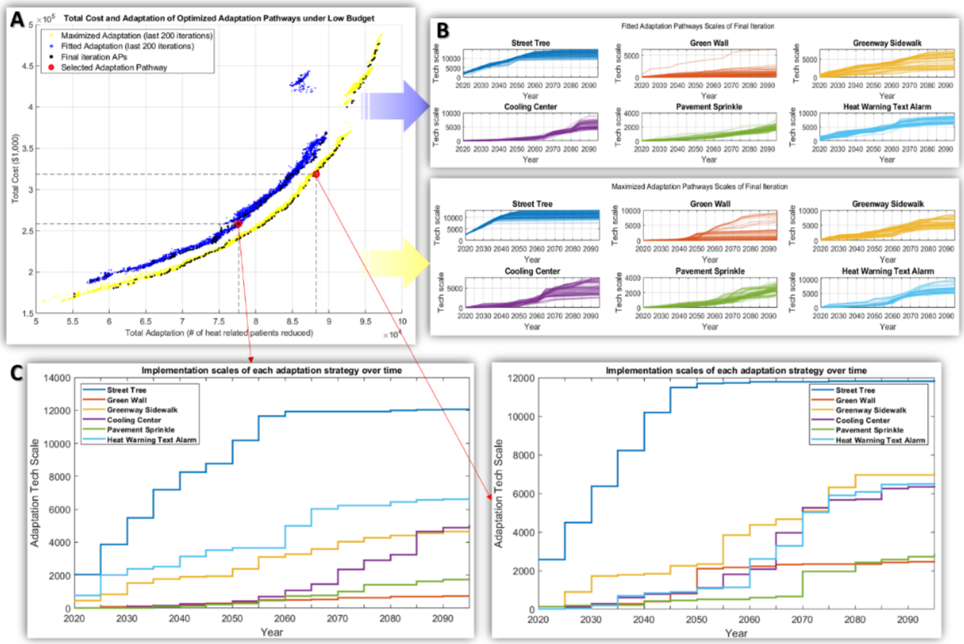

Fig. 20 Representation of individual adaptation pathway selected from a Pareto optimal set. (A) The Pareto optimal set of adaptation pathways identified from our model under low budget setting and two adaptation goals. (B) The range in units implemented of each adaptation option across the entire planning period demonstrates the variations of potential adaptation pathways suitable to a decision-maker's preference. (C) Example of two different adaptation pathways where each adaptation option is represented by a color line and each step indicates the number of units to be implemented for each planning period.

Fig. 20 is an exemplified interactive display of how a decision-maker can explore and ultimately select an adaptation pathway is represented. From our model, the resulting Pareto optimal set includes 200 unique adaptation pathways. Panel B shows the range in number of each adaptation option to be implemented across 2020~2100 of the 200 adaptation pathways in a Pareto optimal set. Panel B is not an information source that is friendly for a decision-maker so they can reference the wide range of optimal options that is available. Using Panel A, a decision-maker can select their preference on the total cost and total adaptation effect and according to the identified Panel C, they can ultimately plan their adaptation implementation plan as it shows when and how much each adaptation option should be implemented.

Under the current setting of the adaptation model and the information availability, the suggested adaptation pathways cannot be directly translated into practice. Therefore, two-tier development of the model architecture, to better model the decision needs and preference settings need to be improved and the input values to be evaluated using the model need to be made available to be used in the local, regional scale decision-making context. Adaptation efforts encompass not only hard, structure-based measures but soft, policy-based measures that boost adaptation capacity and lower vulnerability. Models must make progress to include system simulations that are not based solely on techo-economic assumptions (Eker et al., 2018; Eker, 2021). Current modeling efforts can shift to make more explicit efforts in including diversity and policy relevance in evaluating the so-called plausible futures.

VII. Conclusion

This study derives the optimal adaptation pathway to maximize the total adaptation effect according to decision-maker preferences, multi-sector considerations and portfolio of adaptation options. The search technique used to find the optimal adaptation pathway is based on a heuristic, machine-learning algorithm that finds a Pareto of solutions satisfying multiple objectives including adaptation effect maximization and cost minimization.

Our study found that high budgets do not necessarily lead to optimal adaptation plans and rather lower budget constraints may guide to more efficient adaptation plans for a conservative fitted adaptation goal setting. Under an RCP 8.5 scenario of heat-related mortality in Seoul, South Korea, the current portfolio of adaptation options is not sufficient to fully adapt to impacts after 2065. Furthermore, a delay of no adaptation for more than 10 years leads to insufficient adaptation for the entire planning period (2020~2100).

When considering multi-sector impacts, the cost-benefit trade-off is not uniform across scenarios and sectors. Cost-savings in one sector allows for more adaptation in the other while there is no one answer to ‘better’ adaptation when considering the different sector adaptation effect and costs.

These results suggest that decision preferences can determine the success and failure of adaptation so a careful construction of the goal, constraints and use of scientific information must be holistically considered.

This model not only provides an innovative method to assist decision-making for long-term adaptation planning but also insight into the effects of different adaptation goal settings and economic decisions on an adaptation trajectory. Using this model, a decision-maker can explore how their preferences can translate into a specific adaptation pathway guiding when and how many adaptation options need to be implemented. The efficiency of using a machine-learning algorithm allows for real-time simulation of optimal plans depending on the user's needs and uncertainties – for example, decision makers can modify the search to find a budget constraint that meets their adaptation goal. By developing this model into a user interface, decision-makers will be able to actively engage in developing their adaptation pathway and the usability of this method can be evaluated by actual policy practitioners.

VIII. Bibliography

Agrawala, Shardul, Francesco Bosello, Carlo Carraro, Kelly De Bruin, Enrica De Cian, R. O. B. Dellink, and Elisa Lanzi. 2011. “Plan or React? Analysis of Adaptation Costs and Benefits Using Integrated Assessment Models.” *Climate Change Economics* 2(3):175–208. doi: 10.1142/S2010007811000267.

Babbar-Sebens, M., Minsker, B.S., 2012. Interactive Genetic Algorithm with Mixed Initiative Interaction for multi-criteria ground water monitoring design. Appl. Soft Comput. J. 12, 182–195.

Babbar-Sebens, M., Mukhopadhyay, S., Singh, V.B., Piemonti, A.D., 2015. A web-based software tool for participatory optimization of conservation practices in watersheds. Environ. Model. Softw. 69, 111–127.

Babovic, F., Mijic, A., 2019. Economic evaluation of adaptation pathways for an urban drainage system experiencing deep uncertainty. Water 11.

Barnett, J., O’Neill, S., 2010. Maladaptation. Glob. Environ. Chang. 20, 211–213.

Bartholomew, E., & Kwakkel, J. H., 2020. On considering robustness in the search phase of Robust Decision Making: A comparison of Many-Objective Robust Decision Making, multi-scenario Many-Objective Robust Decision Making, and Many Objective Robust Optimization. Environmental Modelling & Software, 127, 104699.

Basco-Carrera, L., Warren, A., van Beek, E., Jonoski, A., Giardino, A., 2017. Collaborative modelling or participatory modelling? A framework for water resources management. Environ. Model. Softw. 91, 95–110.

Beh, E.H.Y., Maier, H.R., Dandy, G.C., 2015. Adaptive, multiobjective optimal sequencing approach for urban water supply augmentation under deep uncertainty. Water Resour. Res. 51, 1529–1551.

Berry, Pam M., Sally Brown, Minpeng Chen, Areti Kontogianni, Olwen Rowlands, Gillian Simpson, and Michalis Skourtos. 2015. “Cross-Sectoral Interactions of Adaptation and Mitigation Measures.” *Climatic Change* 128(3–4):381–93. doi: 10.1007/s10584-014-1214-0.

Bhave, A., Conway, D., Dessai, S., Stainforth, D., 2016. Barriers and opportunities for robust decision making approaches to support climate change adaptation in the developing world. Climate Risk Management. 14, 1-10.

Bierbaum, Rosina, Joel B. Smith, Arthur Lee, Maria Blair, Lynne Carter, F. Stuart Chapin, Paul Fleming, Susan Ruffo, Missy Stults, Shannon McNeeley, Emily Wasley, and Laura Verduzco. 2013. “A Comprehensive Review of Climate Adaptation in the United States: More than before, but Less than Needed.”

Mitigation and Adaptation Strategies for Global Change 18(3):361–406. doi: 10.1007/s11027-012-9423-1.

Bosomworth, K., Gaillard, E., 2019. Engaging with uncertainty and ambiguity through participatory “Adaptive Pathways” approaches: Scoping the literature. Environ. Res. Lett. 14.

Carlsson-Kanyama, A., Carlsen, H., Dreborg, K.H., 2013. Barriers in municipal climate change adaptation: Results from case studies using backcasting. Futures 49, 9–21.

Casanueva, A., Burgstall, A., Kotlarski, S., Messeri, A., Morabito, M., Flouris, A.D., Nybo, L., Spirig, C., Schwierz, C., 2019. Overview of existing heat-health warning systems in Europe. Int. J. Environ. Res. Public Health 16.

Cash, D., Clark, W.C., Alcock, F., Dickson, N., Eckley, N., Jäger, J., 2003. Salience, Credibility, Legitimacy and Boundaries: Linking Research, Assessment and Decision Making, KSG Working Papers Series.

Casanueva, A., Burgstall, A., Kotlarski, S., Messeri, A., Morabito, M., Flouris, A.D., Nybo, L., Spirig, C., Schwierz, C., 2019. Overview of existing heat-health warning systems in Europe. Int. J. Environ. Res. Public Health 16.

Chapman, S., Thatcher, M., Salazar, A., Watson, J.E.M., McAlpine, C.A., 2019. The impact of climate change and urban growth on urban climate and heat stress in a subtropical city. Int. J. Climatol. 39, 3013–3030.

Chhetri, N., Stuhlmacher, M., Ishtiaque, A., 2019. Nested pathways to adaptation. Environ. Res. Commun. 1, 015001.

Choi, Changsoon, Pam Berry, and Alison Smith. 2021. “The Climate Benefits, Co-Benefits, and Trade-Offs of Green Infrastructure: A Systematic Literature Review.” *Journal of Environmental Management* 291(March):112583. doi: 10.1016/j.jenvman.2021.112583.

Cradock-Henry, N.A., Blackett, P., Hall, M., Johnstone, P., Teixeira, E., Wreford, A., 2020. Climate adaptation pathways for agriculture: Insights from a participatory process. Environ. Sci. Policy 107, 66–79.

de Bruin, K., Dellink, R.B., Ruijs, A., Bolwidt, L., van Buuren, A., Graveland, J., De Groot, R.S., Kuikman, P.J., Reinhard, S., Roetter, R.P., Tassone, V.C., Verhagen, A., van Ierland, E.C., 2009a. Adapting to climate change in the Netherlands: An inventory of climate adaptation options and ranking of alternatives. Clim. Change 95, 23–45.

de Bruin, K.C., R.B. Dellink, and R.S.J. Tol, 2009b, AD-DICE: an implementation of adaptation in the DICE model. Climatic Change, 95 (1-2), 63-81

de Ruig, L.T., Barnard, P.L., Botzen, W.J.W., Grifman, P., Hart, J.F., de Moel, H., Sadrpour, N., Aerts, J.C.J.H., 2019. An economic evaluation of adaptation pathways in coastal mega cities: An illustration for Los Angeles. Sci. Total Environ. 678, 647–659.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evol. Comput. 6, 182–197.

Dessai, S. and M. Hulme, 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: a case study on water resources management in the East of England. Global Environmental Change, 17, 59-72.

Dessai, S., Hulme, M., Lempert, R., Pielke, R., 2009. Climate prediction: a limit to adaptation?, in: Adapting to Climate Change. Cambridge University Press, pp. 64–78.

Eker, S., Rovenskaya, E., Obersteiner, M. *et al.* Practice and perspectives in the validation of resource management models. *Nat Commun* **9,** 5359 (2018). https://doi.org/10.1038/s41467-018-07811-9

Eker, S. Drivers of photovoltaic uncertainty. *Nat. Clim. Chang.* **11,** 184–185 (2021). https://doi.org/10.1038/s41558-021-01002-z

Fonseca, C.M., Paquete, L., Lopez-Ibanez, M., 2006. An Improved Dimension-Sweep Algorithm for the Hypervolume Indicator, in: 2006 IEEE International Conference on Evolutionary Computation. IEEE, pp. 1157–1163.

Founda, D., Varotsos, K. V., Pierros, F., Giannakopoulos, C., 2019. Observed and projected shifts in hot extremes' season in the Eastern Mediterranean. Glob. Planet. Change 175, 190–200.

Giordano, F., Capriolo, A., Mascolo, R.A., 2013. Planning for adaptation to climate change: guidelines for municipalities, LIFE08 ENV/IT/000436.

Gorddard, Russell, Matthew J. Colloff, Russell M. Wise, Dan Ware, and Michael Dunlop. 2016. "Values, Rules and Knowledge: Adaptation as Change in the Decision Context." *Environmental Science and Policy* 57:60–69. doi: 10.1016/j.envsci.2015.12.004.

Haasnoot, M., Kwakkel, J.H., Walker, W.E., ter Maat, J., 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Glob. Environ. Chang. 23, 485–498.

Hamarat, C., Kwakkel, J.H., Pruyt, E., Loonen, E.T., 2014. An exploratory approach for adaptive policymaking by using multi-objective robust optimization. Simul. Model. Pract. Theory 46, 25–39.

Hausfather, Z., & Peters, G. P., 2020. Emissions - the 'business as usual' story is misleading. Nature, 577, 618-620.

Herman, J.D., Reed, P.M., Zeff, H.B., Characklis, G.W., 2015. How should robustness be defined for water systems planning under change? J. Water Resour. Plan. Manag. 141, 1–14.

Hof, A.F., K.C. de Bruin, R.B. Dellink, M.G.J. den Elzen, and D.P. van Vuuren, 2009, The effect of different mitigation strategies on international financing of adaptation. Environmental Science and Policy, 12 (7), 832-843.

Hyun, J.H., Kim, J., Yoon, S., Park, C.Y., Jung, H., Jung, T.Y., Lee, D.K., 2019. A Decision-making Support Strategy to Strengthen Korea’s Local Adaptation Planning toward a Pathways Approach. J. Clim. Chang. Res. 10, 89–102.

ICLEI, 2010. Changing Climate, Changing Communities: Guide and Workbook for Municipal Climate Adaptation. Bonn.

Kim, D.W., Deo, R.C., Chung, J.H., Lee, J.S., 2016. Projection of heat wave mortality related to climate change in Korea. Nat. Hazards 80, 623–637.

Kingsborough, A., Jenkins, K., Hall, J.W., 2017. Development and appraisal of long-term adaptation pathways for managing heat-risk in London. Clim. Risk Manag. 16, 73–92.

Korea Meteorological Agency, 2018. Climate Change Projection Analysis of Korean Peninsula.

Kwadijk, J.C.J., Haasnoot, M., Mulder, J.P.M., Hoogvliet, M.M.C., Jeuken, A.B.M., van der Krogt, R.A.A., van Oostrom, N.G.C., Schelfhout, H.A., van Velzen, E.H., van Waveren, H., de Wit, M.J.M., 2010. Using adaptation tipping points to prepare for climate change and sea level rise: A case study in the Netherlands. Wiley Interdiscip. Rev. Clim. Chang. 1, 729–740.

Kwakkel, Jan H., and Jan Willem G. M. Van Der Pas. 2011. “Evaluation of Infrastructure Planning Approaches: An Analogy with Medicine.” *Futures* 43(9):934–46. doi: 10.1016/j.futures.2011.06.003.

Kwakkel, J. H., Haasnoot, M., & Walker, W. E., 2015. Developing Dynamic Adaptive Policy Pathways: A computer-assisted approach for developing adaptive strategies for a deeply uncertain world. Climatic Change, 132(3), 373-386.

Kwakkel, J.H., Haasnoot, M., Walker, W.E., 2016. Comparing Robust Decision-Making and Dynamic Adaptive Policy Pathways for model-based decision support under deep uncertainty. Environ. Model. Softw. 86, 168–183.

Kwakkel, J.H., 2017. The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. Environ. Model. Softw. 96, 239–250.

Kwakkel, J.H., Haasnoot, M., 2019. Supporting DMDU: A Taxonomy of

Approaches and Tools, in: Decision Making under Deep Uncertainty. Springer International Publishing, Cham, pp. 355–374.

Lee, J.Y., Kim, E., Lee, W.S., Chae, Y., Kim, H., 2018. Projection of future mortality due to temperature and population changes under representative concentration pathways and shared socioeconomic pathways. Int. J. Environ. Res. Public Health 15, 1–9.

Lee, J.Y., Kim, H., 2016. Projection of future temperature-related mortality due to climate and demographic changes. Environ. Int. 94, 489–494.

Lempert, R.J., Groves, D.G., Popper, S.W., Bankes, S.C., 2006. A general, analytic method for generating robust strategies and narrative scenarios. Manage. Sci. 52, 514–528.

Maier, H. R., J. H. A. Guillaume, H. van Delden, G. A. Riddell, M. Haasnoot, and J. H. Kwakkel. 2016. “An Uncertain Future, Deep Uncertainty, Scenarios, Robustness and Adaptation: How Do They Fit Together?” *Environmental Modelling and Software* 81:154–64. doi: 10.1016/j.envsoft.2016.03.014.

Min, S.K., Son, S.W., Seo, K.H., Kug, J.S., An, S. Il, Choi, Y.S., Jeong, J.H., Kim, B.M., Kim, J.W., Kim, Y.H., Lee, J.Y., Lee, M.I., 2015. Changes in weather and climate extremes over Korea and possible causes: A review. Asia-Pacific J. Atmos. Sci. 51, 103–121.

Mullaney, J., Lucke, T., Trueman, S.J., 2015. A review of benefits and challenges in growing street trees in paved urban environments. Landsc. Urban Plan. 134, 157–166.

Nay, J. J., Abkowitz, M., Chu, E., Gallagher, D., & Wright, H., 2014. A review of decision-support models for adaptation to climate change in the context of development. Climate and Development, 6(4), 357-367.

Nordgren, J., Stults, M., Meerow, S., 2016. Supporting local climate change adaptation: Where we are and where we need to go. Environ. Sci. Policy 66, 344–352.

O’Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change 42, 169–180.

Owen, G., 2020. What makes climate change adaptation effective? A systematic review of the literature. Glob. Environ. Chang. 62, 102071.

Park, C.Y., Lee, D.K., Hyun, J.H., 2019. The effects of extreme heat adaptation strategies under different climate change mitigation scenarios in Seoul, Korea. Sustain. 11.

Park, C.Y., Yoon, E.J., Lee, D.K., Thorne, J.H., 2020. Integrating four radiant heat load mitigation strategies is an efficient intervention to improve human health in urban environments. Sci. Total Environ. 698, 134259.

Pedersen, J.T.S., Santos, F.D., Vuuren, D. van, Gupta, J., Coelho, R.E., Aparício, B.A., Swart, R., 2020. An Assessment of the Performance of Scenarios against Historical Global Emissions for IPCC Reports. Glob. Environ. Chang. 66.

Preston, Benjamin L., Richard M. Westaway, and Emma J. Yuen. 2011. *Climate Adaptation Planning in Practice: An Evaluation of Adaptation Plans from Three Developed Nations*. Vol. 16.

Quinn, J. D., Reed, P. M., Giuliani, M., & Castelletti, A., 2017. Rival framings: A framework for discovering how problem formulation uncertainties shape risk management trade-offs in water resources systems. Water Resources Research.

Quinn, J. D., A. Hadjimichael, P. M. Reed, and S. Steinschneider. 2020. "Can Exploratory Modeling of Water Scarcity Vulnerabilities and Robustness Be Scenario Neutral?" *Earth's Future* 8(11):1–25. doi: 10.1029/2020EF001650.

Rapley, C., de Meyer, K., Carney, J., Clarke, R., Howarth, C., Smith, N., Stilgoe, J., Youngs, S., Brierley, C., Haugvaldstad, A., Lotto, B., Michie, S., Shipworth, M., Tuckett, D., 2014. Time for Change? Climate Science Reconsidered, Report of the UCL Policy Commission on Communicating Climate Science.

Reis, J., Shortridge, J., 2019. Impact of Uncertainty Parameter Distribution on Robust Decision Making Outcomes for Climate Change Adaptation under Deep Uncertainty. Risk Analysis, 40(3), 494-511.

Scheraga, J.D., Grambsch, A.E., 1999. Risks, opportunities, and adaptation to climate change. Clim. Res. 11, 85–95.

Schipper, E.L.F., 2009. Meeting at the crossroads?: Exploring the linkages between climate change adaptation and disaster risk reduction. Clim. Dev. 1, 16–30.

Seoul Metropolitan Government, 2017. Implementation Plan for Climate Change Adaptation Strategy. Seoul.

Shah, A.K., Oppenheimer, D.M., 2008. Heuristics Made Easy: An Effort-Reduction Framework. Psychol. Bull. 134, 207–222.

Smithers, J., Smit, B., 1997. Human adaptation to climatic variability and change. Glob. Environ. Chang. 7, 129–146.

Susaki, Junichi, and Seiya Kubota. 2017. “Automatic Assessment of Green Space Ratio in Urban Areas from Mobile Scanning Data.” *Remote Sensing* 9(3). doi: 10.3390/rs9030215.

Tanaka, A., Takahashi, K., Masutomi, Y., Hanasaki, N., Hijioka, Y., Shiogama, H., Yamanaka, Y., 2015. Adaptation pathways of global wheat production: Importance of strategic adaptation to climate change. Sci. Rep. 5, 2–11.

Trindade, B. C., Reed, P. M., Herman, J. D., Zeff, H. B., & Characklis, G., 2017. Reducing regional drought vulnerabilities and multi-city robustness conflicts using many-objective optimization under deep uncertainty. Advances in Water Resources.

Trindade, B. C., Reed, P. M., & Characklis, G. W., 2019. Deeply Uncertain Pathways: Integrated Multi-City Regional Water Supply Infrastructure Investment and Portfolio Management. Advances in Water Resources.

Vij, S., Moors, E., Ahmad, B., Uzzaman, A., Bhadwal, S., Biesbroek, R., Gioli, G., Groot, A., Mallick, D., Regmi, B., Saeed, B.A., Ishaq, S., Thapa, B., Werners, S.E., Wester, P., 2017. Climate adaptation approaches and key policy characteristics: Cases from South Asia. Environ. Sci. Policy 78, 58–65.

Walker, W.E., Haasnoot, M., Kwakkel, J.H., 2013. Adapt or perish: A review of planning approaches for adaptation under deep uncertainty. Sustain. 5, 955–979.

Ward, V. L., Singh, R., Reed, P. M., & Keller, K., 2015. Confronting tipping points: Can multi-objective evolutionary algorithms discover pollution control tradeoffs given environmental thresholds? Environmental Modelling & Software, 73(1), 27-43.

Williams, D. S., Costa, M. M., Kovalevsky, D., Hurk, B. V., Klein, B., Meißner, D., Pulido-Velazquez, M., Andreu, J., Suárez-Almiñana, S., 2020. A method of assessing user capacities for effective climate services. Climate Services, 19, 100180.

Wise, R.M., Fazey, I., Stafford Smith, M., Park, S.E., Eakin, H.C., Archer Van Garderen, E.R.M., Campbell, B., 2014. Reconceptualising adaptation to climate change as part of pathways of change and response. Glob. Environ. Chang. 28, 325–336.

Woodruff, M. J., Reed, P. M., & Simpson, T. W., 2013. Many objective visual analytics: rethinging the design of complex engineered systems. Structural and multidisciplinary optimization, 48, 201-219.

Yamin, F., Rahman, A., Huq, S., 2005. Vulnerability, adaptation and climate disasters: A conceptual overview. IDS Bull. 36, 1–14.

Yang, H.J., Yoon, H., 2020. Evaluating the Effectiveness of Heat-Wave Adaptation Policies against Climate Risk: Application of Local-Level Health Impact Assessment. J. Korea Plan. Assoc. 55, 101–110.

Yoon, E.J., Kim, B., Lee, D.K., 2019. Multi-objective planning model for urban greening based on optimization algorithms. Urban For. Urban Green. 40, 183–194.

Zandvoort, M., Campos, I.S., Vizinho, A., Penha-Lopes, G., Lorencová, E.K., van der Brugge, R., van der Vlist, M.J., van den Brink, A., Jeuken, A.B.M., 2017. Adaptation pathways in planning for uncertain climate change: Applications in Portugal, the Czech Republic and the Netherlands. Environ. Sci. Policy 78, 18–26.

Zatarain Salazar, J., Reed, P. M., Herman, J. D., Giuliani, M., & Castelletti, A., 2016. A diagnostic assessment of evolutionary algorithms for multi-objective surface water resevoir control. Advances in Water Resources, 92(172-185).

Zölch, T., Henze, L., Keilholz, P., Pauleit, S., 2017. Regulating urban surface runoff through nature-based solutions – An assessment at the micro-scale. Environ. Res. 157, 135–144.

Abstract in Korean

기후변화 적응계획 의사결정지원을 위한 적응경로 탐색 모델 개발

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기후변화 적응은 미래에 가속화될 기상변화에 대응하기 위해 다양한 시나리오에 따른 기후 영향을 현재 시점에서 분석하고, 잠재적인 적응 옵션을 확인하며, 정책 결정 과정에서 제기될 수 있는 의문들을 식별할 수 있어야 한다. 그러나 기후적응의 중요성이 부각됨에도 불구하고, 실제로 이행된 적응정책은 상대적으로 적다. 이행 부족의 원인으로는 미래에 대한 예측이 어렵고, 이에 대비할 수 있는 최적의 대응책이 무엇인지를 판단하기 위한 정보가 부족하며, 판단할 수 있는 명확한 방법이 없다는 점을 들 수 있다. 기후변화 적응정책의 특성상 다양한 이해관계자가 관여되어 있고 막대한 비용이 소요된다. 그럼에도 적응계획을 세울 때 다양한 이해관계자들을 설득하

고 지지를 얻기 위해서는 합리적으로 판단을 내릴 수 있는 정책평가 자료가 필요하다. 따라서 기후변화 적응정책을 효율적으로 이행하기 위해서는 정책에 대한 명확한 이해와 객관적인 평가가 바탕이 되어야 하지만 정성적인 판단으로 정책이 수립되고 있을 뿐, 정책 효과의 정량적인 판단이 이루어지지 않고 있다. 따라서 본 연구는 미래 피해에 따른 적응대책별 효과를 대입하는 탐색적 모델을 개발하여 적응계획에서 활용할 수 있도록 하는 것을 목표로 한다.

본 연구의 주요 목표는 상대적 비용 효율성과 효과적인 기후 영향 감소를 달성하는 최적의 적응경로의 파레토를 식별할 수 있는 탐색적 계획 모델을 개발하는 것이다. 적응경로는 16개의 연속된 5년단위의 계획 기간으로 구성되어 있으며 각 계획 기간별로 각 적응기술의 규모가 조정될수 있다. 우수한 적응경로는 미래의 기후영향을 더 적응하거나 비용을 낮추면 선택되도록 모델을 설계 하였다. 다양한 적응경로를 탐색하기 위해 다목적 최적화 방법으로 머신러닝 기반 진화 알고리즘인 비지배적 정렬 유전 알고리즘(NSGA-II)을 사용하였다.

먼저, 적응경로 모델을 소개하고 이를 두 가지 의사결정 문제에 적용한다.

두 가지 의사결정 문제는 1) 전략적 목표 설정과 2) 이행과제 우선순위 선정이다. 첫 번째 모델 적용 사례에서는 제약 조건 및 적응 목표를 사전 설정된 값으로 고정하는 대신 의사결정자의 선호도를 매개화 하여 다양한 시나리오를 탐구한다. 본 사례에서는 도시에서의 폭염 관련 상병자를 줄이기 위해 직접적인 적응대책(상병자 수 저감)과 간접적인 적응대책(옥외 열환경 개선)을 적용했다. 목표 설정 옵션을 탐구하기 위해, 다양한 예산 및 영향 감축 방식을 평가하였다. 두 번째 사례의 경우, 적응경로 모델을 수정하여 다른 미래 완화 정책 목표 시나리오(RCP 2.6은 1.5°C 증가 한계를 나타내고, RCP 4.5는 2°C 증가 한계를 나타내고, RCP 8.5는 가장 높은 배출 시나리오)에 따라 다부문 위험을 평가하였다. 도시 열과 홍수 영향을 줄이기 위해 그린인프라 기반 적응 기술의 효과를 확인하였다.

첫 번째 모델 적용 사례에서는 우수한 적응경로는 미래의 기후 영향에 적응할 수 있거나, 적응 비용이 적은 경우에 선택되도록 모델을 설계하였다. 특히, 의사결정자의 선호도(제약 조건 및 적응목표)에 따라 도시에서의 폭염 관련 상병자를 줄이기 위해 직접적인 적응 효과(상병자 수 저감)와 간접적인 적응대책(그린인프라를 통한 옥외 열 환경 개선)을 적용하여 RCP 4.5와

8.5 시나리오에서의 최적의 적응계획을 살펴보았다. 먼저, 예산이 높다고 해서 반드시 최적의 적응계획으로 이어지지 않았으며, 오히려 낮은 예산 조건에서 적응목표 설정에 따라 비교적 더 효율적인 적응계획이 도출되었다. RCP 8.5 시나리오에서는 현재의 적응 옵션 포트폴리오로는 2065년 이후의 영향에는 완전히 적응하기에 불충분한 것으로 분석되었다. 또한, 10년 이상 적응 행동을 지체하게 되면 이후에는 적응이 불가능하다. 마지막으로 그린인프라는 시간에 따라 적응 효과가 증폭되어, 증가하는 미래 영향을 저감하는 데에 효과적인 적응기술임이 검증되었다.

도시의 폭염과 홍수의 미래 영향을 줄이기 위해 그린인프라 기반 적응기술의 효과와 효율성은 복합적인 것으로 확인되었다. 부문 우선순위에 따라 비지배적 최적화된 적응 경로를 정렬할 때 가장 비용 효율적인 경로가 최적으로 식별되었다. 비용 효율성은 미래의 영향 수준과 그린인프라 기술의 비용 절충에 민감했다. RCP 2.6의 영향은 RCP 4.5에 비해 적기 때문에 규모의 경제로 인해 현재 적응 기술이 비용효율적이지 않아 적응을 덜 하게 되는 적응경로들이 최적화되는 결과가 나왔다. 그린인프라 기반 기술의 증가하는 효과는 적응 경로 모델이 RCP 2.6 시나리오에서 고려하기 어려웠으

며 2050년 이전에는 과소적응, 2050년 이후에는 과잉 부적응을 초래했습니다. 그린인프라 기반 적응에 대한 사회적 할인율의 영향은 다음과 같습니다. 비용 보조금이 물 부문의 기술에 투자를 늘리기 위한 추가 자원을 제공하는 경우 간접적인 효과가 있었다.

이러한 결과는 적응을 위한 계획에서 다차원을 고려할 필요가 있음을 시사하고 불확실성 하에서 보다 명확한 의사 결정을 위한 기반으로 탐색적 모델링을 사용하는 이점을 보여한다. 이 연구의 전반적인 결과는 적응 경로 모델링에 대한 연구와 의사 결정 기반 적응 계획 지원 도구 간의 격차를 메웁니다. 두 경우의 결과는 적응계획을 위한 의사결정 방법을 적용할 때 참고할 수 있다.

주요어: 기후변화, 적응계획, 불확실성 하에 의사결정, 최적화, 탐색적 모델

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