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Discussions

Multi-scenario multi-objective analysis of downscaled shared socio-economic pathways (SSPs) for robust policy development in coupled human-water systems

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Abstract. Shared socio-economic pathways (SSP) scenario analysis is concerned with developing climate change adaptation strategies that perform well across a wide range of plausible future socio-economic and climate change conditions. However, downscaled/localized SSP scenarios, most relevant for regional climate adaptation, are poorly understood in terms of their deep uncertainties and how these scenarios can contribute to the development of robust regional policies in coupled human-water systems. In the present study, we propose a new framework that integrates a multi-scenario multi-objective (meta-criteria) optimization analysis of a set of downscaled/localized SSP storylines with the robust decision-making concept to find optimal robust solutions under deep uncertainty concerning regional climate adaptation. By developing an integrated dynamic simulation-optimization model, potential policy alternatives are investigated, and their robustness evaluated based on four key objectives: farm income, groundwater depletion, soil salinity, and reliability. Scenario-based multi-objective optimization for multiple SSP scenarios is merged into a robust optimization problem and evaluated in parallel. The proposed framework is applied to study potential robust solutions for vulnerabilities of a real-world human-water system in Pakistan's Rechna Doab region that has multiple stakeholders and conflicting objectives. The results revealed Pareto optimal solutions that are both optimally feasible and robustly efficient. The socio-environmental conditions of SSPs have a significant influence on the estimated robustness. The candidate solutions under scenario SSP1 are remarkably comparable to those offered by scenario SSP5, which was deemed to be the best among the SSPs evaluated. SSP3 was the least desirable of the SSP scenarios examined and solutions resulted in undesirable soil salinity, groundwater depletion, and reliability values. By incorporating SSP narratives and quantitative scenario analysis, the proposed framework revealed advantages for integrated dynamic modelling of human-water systems with a high level of uncertainty and complex interconnections to discover robust climate change adaptation solutions.

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1 Introduction

Scenarios are an integral part of climate change research since they provide a framework to characterize uncertainty when developing policies regarding complex human-water systems. Their purpose is to provide insight into how the future might unfold under a variety of hypothetical but expected conditions, or how desirable outcomes may be achieved, and unpleasant ones avoided by undertaking specific measures (O'Neill et al., 2020). A wide variety of climate change and societal future scenario analyses have been used across the climate change research community, and have contributed to global and regional policy-making (O'Neill et al., 2020). Model-based scenario analysis can be a useful tool to explore alternative futures based on various social and environmental factors in coupled socio-environmental systems characterized by complex behaviour and interactions. Shared Socio-economic Pathways (SSPs) (Riahi et al., 2017) are a series of community-based scenarios that analyse alternative socio-environmental trajectories, particularly in relation to socio-economic development, energy system development, agricultural activities, and water usage. Various integrated assessment models have been used to implement SSPs (van Vuuren et al., 2017; Alizadeh et al., 2022a; Beusen et al., 2022). Climate and societal futures can be analysed simultaneously within an SSP framework, resulting in integrated climate change scenarios. Furthermore, downscaled/localized SSPs have been used to inform decision-makers about local adaptation and mitigation strategies at various temporal and spatial scales (Kok et al., 2019; Iqbal et al., 2019; Gao et al., 2021; Reimann et al., 2021). Recently-developed architectures for downscaled SSP scenarios have enabled us to overcome some of the most significant challenges in basic SSP scenarios. Through the downscaled scenario paradigm, a variety of technical, socio-economic, and policy prospects that may lead to beneficial adaptation pathways can be envisioned at regional scales (Guivarch et al., 2016).

It is assumed that SSP scenarios are not associated with ~~accurate~~ probabilities, a ~~poorly understood~~ condition known as deep uncertainty (Miettinen, 2012). Policy formulation in complex human-water systems utilizing such downscaled SSP scenarios is therefore significantly hampered by deep uncertainty (Bankes, 2002; Kwakkel et al., 2010; Walker et al., 2013). Two important sources of deep uncertainty in the SSP framework are future changes in climate and socio-economic conditions. As the future is extremely unpredictable in terms of social, economic, and environmental factors, it is vital to evaluate policies with numerous scenarios that encompass a wide range of possible outcomes (Hallegatte 2009; Lempert 2013). Adopting a climate adaptation strategy that works in a specific scenario but not in the others is extremely risky; for instance, in the case where the population is greater than expected or technology advances are slower than anticipated. Despite the consistent plausibility of SSP scenarios, this does not guarantee that their outcomes will span the uncertainty spectrum that policymakers desire in terms of varying socio-economic and climate change impacts (e.g., GDP or GHG emissions) (Rozenberg et al., 2014). As a result, for some applications of scenario analysis, it may be necessary to investigate socio-economic factors that contribute to specific outcomes (Guivarch et al., 2016; O'Neill et al., 2017).

In recent years, various strategies have been developed to enhance the potential of the new SSP scenario architecture. For example, Ebi et al. (2014) recommended creating and utilizing massive databases of possible scenarios to facilitate the selection of in-depth, self-consistent scenarios that are tailored to their unique situations. Additionally, clustering techniques were

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applied to databases of many model simulations to identify scenarios pertinent to specific strategy concerns with less likelihood of uncertainty than what would be apparent from narrative or simulation methodologies (McJeon et al., 2011; Haasnoot et al., 2013; Hamarat et al. 2013). The concept of "backward" analysis has been used in SSP scenarios to account for uncertainties and map out the space of potential future complexities for mitigation and adaptation (Rozenberg et al., 2014). Scenario discovery analysis has also been used to handle SSP scenario uncertainties (Guivarch et al., 2016). However, the challenge is to find solid policies that perform well under social and environmental changes in SSPs, while controlling the multiplicity of potential uncertainties. In such complex socio-environmental systems, there is a high level of deep uncertainty and the probability for the diverse socio-economic situations in the SSP can only be roughly estimated. All objectives specified in all plausible scenarios should be considered when evaluating the effectiveness of a strategy (Stewart et al., 2013; Shavazipour and Stewart, 2021). Therefore, a successful policy should not only achieve social, economic, and environmental objectives, but it also must be dynamically robust, i.e., it must respond properly to a variety of futures and be flexible enough to handle ever-changing situations (Haasnoot et al., 2011; Maier et al., 2016; Kwakkel et al., 2016).

Since decision makers seek robust solutions appropriate for a broad set of circumstances, Pareto optimality and feasibility in a particular SSP scenario must be balanced against robustness across all SSP scenarios. When such complex human-water problems are presented, policy making can be considered as a multi-scenario multi-objective optimization problem. These decision-problem types are also known as scenario-based multi-objective decision problems (Watson and Kasprzyk, 2017; Eker and Kwakkel, 2018; Shavazipour et al., 2021). When dealing with SSP scenarios, scenario-based multi-objective optimization frameworks can be used to deal with deep uncertainty and consider the consequences of possible policies in making a decision that is sustainable, robust, and adaptable. In recent years, different methods have been proposed for solving multi-objective environmental optimization problems under deep uncertainty, including Multi-Objective Robust Decision Making (MORDM) (Kasprzyk et al., 2013), Multi-Scenario MORDM (Watson and Kasprzyk 2017), and Multi-Objective Robust Optimization (MORO) (Hamarat et al., 2014; Kwakkel et al., 2015). These approaches all involve an iterative process in which predetermined solutions are subjected to a variety of evaluations to establish the conditions under which they fail to operate properly. Considering these failure situations, policy alternatives are revised to identify the most robust solutions. However, these techniques have not yet been evaluated for their effectiveness in SSP scenario studies.

To assist in addressing deep uncertainty in climate adaptation planning under a variety of plausible SSP scenarios, robust policy-making approaches employing different modelling approaches to evaluate downscaled SSP scenarios must be developed and examined. There are no studies in the literature that attempt to understand the effect of deep uncertainty on the robustness values of various policy alternatives within the context of localized SSP scenarios. We address this need by investigating robust policies under the plausibility of some developed localized SSP scenarios. At the same time, we consider deep uncertainty by applying a multi-scenario multi-objective optimization robust analysis (meta-criteria analysis) through an integrated system dynamics simulation-optimization model that simulates the vulnerabilities of a complex human-water system.

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The aim of this study is to provide support for policy-making by linking the concepts of multi-scenario multi-objective optimization analysis (meta-criteria analysis) of downscaled/localized SSP scenarios with the principles of robust decision-making. We present an integrated dynamic simulation-optimization ~~model built by incorporating~~ deep uncertainty in the optimization phase ~~of an integrated dynamic model and identifying~~ policies that function well under a set of downscaled SSPs. The performance of solutions is evaluated in the integrated dynamic model in terms of all objectives in SSP scenarios. As a result, Pareto-optimal solutions can be identified in SSP scenarios that are possible, robust, and efficient. By considering all downscaled SSP scenario objectives, as well as scenario-specific constraints within the optimization phase, the proposed ~~model~~ evaluates candidate policies. Scenario-based multi-objective optimization problems for multiple SSP scenarios are merged into a meta-optimization problem and evaluated in parallel. For all SSP scenarios, the objective functions encompass all objective-scenario combinations that satisfy constraints (meta-objective/meta-criteria) (Stewart et al., 2013).

The proposed framework is used to assess potential robust policies under a variety of localized SSP scenarios for human-water related vulnerabilities within the Rechna Doab region of Pakistan, which serves as an example of a multi-stakeholder coupled human-water system. In so doing, downscaled SSP scenarios were evaluated to identify solutions that are practical under various socio-economic conditions and are also efficient. This study paves the way for future research into the issues surrounding Pareto optimality and robustness. We introduce a novel method of scenario analysis for downscaled SSP narratives to examine the feasibility and robustness of solutions in various SSP scenarios. To gain an understanding of human-water systems in developing countries, this study focused on Pakistan's Rechna Doab watershed, which represents a significant human-water nexus. The human-water system in Rechna Doab offers an ideal option to test, evaluate, and review the efficacy of the suggested meta-criteria analysis framework for local SSP scenarios.

The structure of the paper is as follows: in section 2, we present the study area and its unique characteristics pertinent to our research. Section 3 then provides a comprehensive description of our proposed methodology. The findings of our study are presented in Section 4. Our discussion of the results is presented in section 5, and our conclusion is provided in section 6.

2 Study Area

Situated between the Ravi and Chenab Rivers in central-northeast Pakistan, the Rechna Doab watershed covers 732.5 km^2 (Figure. 1). Irrigated areas in Pakistan's Punjab region are among the oldest and most specialized in the world. During the summer months (Kharif), the most important crops are rice (Oryza sativa L.), cotton (Gossypium hirsutum L.) and forages, while during the winter months (Rabi), the most important crops are wheat (Triticum aestivum L.), tomato (Solanum lycopersicum L.) and forages. The summer (April to September) temperature ranges between 21°C and 49°C, which means a long, hot season. The winter months last from December through February, when daily temperatures range from 25°C to 27°C, and the lowest temperatures may fall below 0°C. The monsoon season, from June to September, is responsible for roughly 75% of the 400 mm of annual precipitation (Ahmad, 2002; Inam et al., 2017a, b). Due to a lack of surface water, farmers use groundwater to irrigate their crops (Arshad et al., 2019). Prolonged droughts have made groundwater the most reliable source of water for industrial, agricultural, and domestic use. However, excessive groundwater extraction has caused a drastic

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reduction in groundwater levels and quality, resulting in salinity issues in some areas of Rechna Doab due to irrigation with saline water and limitations with drainage and salt management even in areas irrigated with freshwater or low-salinity water. This has caused environmental and agricultural productivity constraints stemming from large-scale salinization of land and water resources as well as land subsidence. Disposal of untreated or inadequately treated wastewater to water bodies is common in the study area due to the lack of investments on collection, treatment, and safe reuse or disposal of wastewater from settlements. Such disposal has introduced a range of pollutants – metals and metalloids, emerging contaminants, pathogens – with impacts on environmental and human health (Murtaza et al., 2010).

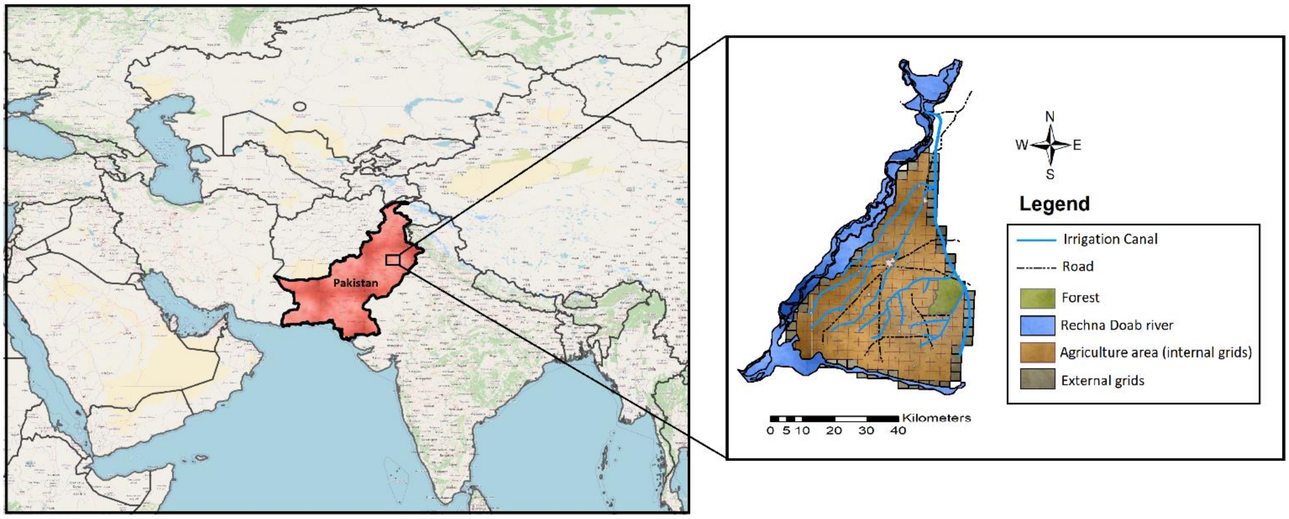

Figure 1: Location of the Rechna Doab watershed within Pakistan (left panel) (© OpenStreetMap contributors 2017. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.) and the human-water system of the Rechna Doab watershed with a grid-based layout of a distributed model map (right panel).

3 Methods

3.1 Integrated socio-economic and environmental system dynamics (ISESD) model

This study employs an integrated dynamic model to simulate plausible downscaled SSP scenario narratives derived from stakeholder input from an earlier phase of this project. The model provides quantitative insights to analyse and identify policy options based on socio-economic and climate conditions. The model employed is an integrated socio-economic and environmental system dynamics (ISESD) model designed to analyse socio-economic and climatic effects and any associated vulnerabilities for climate change adaptation and mitigation at the local scale. The model is composed of two primary components: (i) a physically-based simulation of the hydrological processes of the water system (e.g., groundwater, soil salinity, agricultural yield, etc.) and (ii) a system dynamics simulation of the human system (e.g., population, income, awareness, etc.). The ISESD model is based on coupling a Group-Built System Dynamics Model (GBSDM), developed in a participatory manner with stakeholders, and the Spatial Agro Hydro Soil Salinity and Groundwater Model (SAHYSMOD) using the Tinamït coupling wrapper (Inam et al., 2017a, 2017b; Malard et al., 2017). Through the Tinamït coupling wrapper (Malard et al., 2017), the system dynamics model (GBSDM) developed with stakeholders, which focuses on human behaviour, is linked to the physically-based (P) simulator of hydrological processes (SAHYSMOD). The P-GBSDM model was developed in a previous phase of this research (Inam et al., 2017a, 2017b; Malard et al., 2017; Alizadeh et al., 2022a) and consists of five primary modules: water, economic, agriculture, environment, and policy analysis.

Agricultural data (e.g., crop areas, cropping intensities and duration, as well as yield) and water consumption data (e.g., demand, combinations, and leaching, drainage, evaporation) are calculated by the Agricultural module. Analyses of farm incomes, costs, produce market prices, inflation rates and governmental loans are included in the Economic module. The Water module addresses water demands, irrigation applications, groundwater abstraction, surface water storage, irrigation efficiency, etc. The Policy Analysis module assesses alternative management and adaptation policies proposed by stakeholders during the earlier participatory modelling phase of this project (Inam et al., 2017a, b; Malard et al., 2017; Alizadeh et al., 2022a). The Environment module calculates changes in water quality, soil salinity, and groundwater depletion. Additionally, a variety of financial and environmental restrictions are considered. Moreover, system dynamics simulation of the human behaviour of the integrated model includes numerous social variables (e.g., rate of population change, gross domestic product, rate of technical change, environmental awareness, and human behaviour). In a holistic representation of the human-water system, the main modules and sub-modules (e.g., seepage, effective rainfall, groundwater abstraction, canal linings, irrigation efficiency, storage of surface water, agricultural water demands, domestic water demands, and industrial water demands) are dynamically interconnected via mutual feedbacks.

Figure. 2. shows the main components of the regional ISESD model, with their key submodules. Using an interactive, participatory, and system dynamics approach, the ISESD model provides stakeholders and decision-makers with a comprehensive understanding of the impacts of socio-economic and climatic change on the system and trade-offs associated with various adaptation options as a potential response. The ISESD's contribution to the literature is its holistic framework, which advances integrated model applications through: (i) an expanded analysis of intersectoral links and dynamic interactions involving key sectors (environment, socio-economics, agriculture, water, and policies); (ii) analysis of both the socio-economic and climatic aspects; and (iii) multi-scale applications (bringing together local/regional scale and global scale applications).

The ISESD model is coupled with the scenario-based multi-objective optimization component during the optimization phase of the robust decision-making framework, to develop a fully integrated dynamic simulation-optimization model. This model is then used to assimilate and evaluate candidate policy options across downscaled SSP scenarios and to assess the robustness of the performance of solutions under four defined objectives in SSP scenarios.

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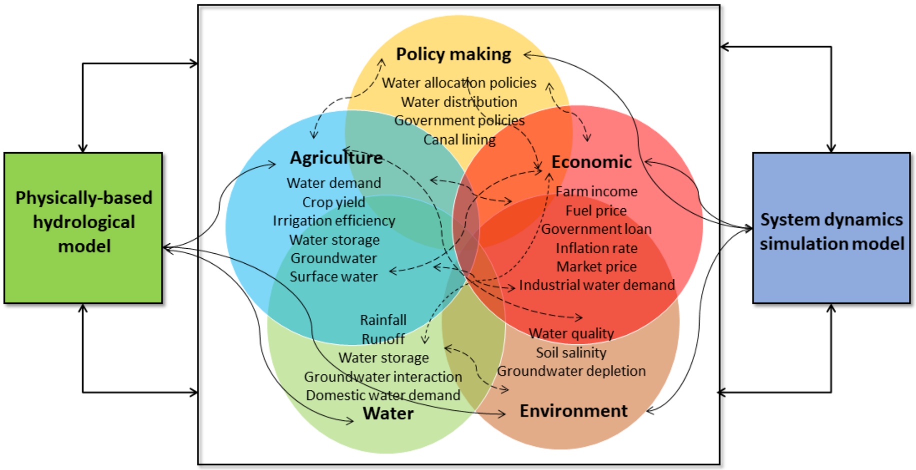

Figure 2: Description of the main components of the regional ISESD model, with their key submodules

3.2 Identifying narrative-informed scenarios and deep uncertainties

To accommodate expected social trends, climate projections need to be downscaled and localized. Therefore, regional/local analyses and quantifications of the possible future climate and socio-economic combinations are essential. As part of the first phase of this research project, we developed a participatory storytelling methodology to extract stakeholders' narratives and scenarios, and developed a set of downscaled SSPs scenarios (Alizadeh et al., 2022a). A scenario development approach (Alcamo & Henrichs, 2008; Rounsevelll & Metzger, 2010) was used to derive local storyline narratives. We used global SSPs as boundary conditions when combining top-down and bottom-up principles in our downscaled SSP scenario generation. Based on the characteristics of global SSPs, regional/local SSPs were developed using a top-down approach.

To map global SSP storylines onto local narrative scenarios, we implemented Zurek and Henrichs' (2007) one-to-one mapping method. A comprehensive analysis was conducted by mapping local narrative scenarios and global SSPs. By analysing how SSP variables changed over time, it was possible to elucidate how socio-economic development changed in the 20th century at the local scale. This analysis led to the identification of socio-economic drivers that shaped aspects of local SSPs. According to stakeholder perceptions of the changes indicated in their storylines, as well as their visions of what might occur, the plausibility of narratives for local adaptation planning was emphasized and evaluated (Voros, 2003; Alizadeh et al., 2021). A set of socio-economic development factors were identified at the regional/local level. Following the selection of key factors pertinent to Rechna Doab, local features that were major drivers of human-water development in the region were carefully incorporated. Nine key uncertain socio-economic and climatic drivers were identified at the local level by analysing the variables included in the integrated model. Table 1 outlines the most uncertain socio-economic and climate drivers and their magnitudes, as derived from our local SSP scenarios in relation to the five downscaled narratives of socio-economic and

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environmental drivers in the region. We have chosen the indicators in Table 1 to ~~illustrate the broad spectrum of interactions as well as to~~ provide plausible future change strategies based on SSPs. For a detailed discussion of these localized narratives, their characteristics, and the explanation of their development, see Alizadeh et al. (2022a).

Table 1. Storyline elements and main uncertain drivers of the five downscaled SSP narratives.

Driver	Units	Localized SSP No.				
		1	2	3	4	5
Climatic						
Δ Temperature	C° yr^{-1}	0.04	0.08	0.10	0.15	0.30
Δ Precipitation	% yr^{-1}	0	-0.05	-0.10	-0.25	-0.40
Socio-economic						
Δ Irrigated area	% yr^{-1}	0.04	0.07	0.40	0.45	0.75
Δ Crop intensity	% yr^{-1}	0.10	0.18	0.25	0.30	0.50
Δ Irrigation efficiency	% yr^{-1}	0.05	0.10	0.18	0.25	0.40
Δ Industrial water intensity	m^3 yr^{-1} $(MW{\cdot}h)^{-1}$	2.50	1.50	0	-2.50	-3.00
Δ Domestic water intensity	L $person^{-1}$ day−1 yr^{-1}	-2.50	-1.50	0	0.50	1.50
Environmental consciousness	—	Very low	Low	Medium	High	Very high
Technology development	—	Very low	Low	Medium	High	Very high

Local SSPs are deeply uncertain in terms of their future climate change and socio-economic conditions. Table 2 presents the range of uncertainty for the most critical socio-economic and climate drivers of the human-water system, based on the five narratives we identified in our local SSP development. Detailed explanations of the quantification of uncertainty bounds for the major deeply uncertain drivers can be found in Alizadeh et al. (2022b).

Table 2. Deeply uncertain variable ranges resulting from downscaled SSPs.

Description	Uncertainty boundaries
Climate drivers	
Temperature change (C° yr^{-1})	[0.02, 0.5]
Precipitation change (% yr^{-1})	[-0.5, 0.05]
Socio-economic drivers	

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Irrigated area growth (% yr^{-1})	[0.01, 0.8]
Crop intensity change (% yr^{-1})	[0.05, 0.6]
Irrigation efficiency change (% yr−1)	[0.01, 0.5]
Industrial water intensity change [m^3 yr^{-1} $(MW{\cdot}h)^{-1}$].	[-4, 3]
Domestic water intensity change (L $person^{-1}$ day^{-1} yr^{-1})	[-3, 2.5]

3.3 Meta-criteria analysis: Multi-scenario multi-objective robust policy making approach

In the present study, downscaled SSP scenarios were employed as an additional factor in the meta-criteria analysis (Stewart et al., 2013) to investigate probability under deep uncertainty and to construct a multi-scenario-based multi-objective structure that could provide robust policies. In the multi-scenario-based model of multi-objective policy making in coupled human-water systems, policies should be considered as dimensions of interests based on the conditions in each SSP scenario. Solutions in uncertain scenarios should be compared according to their performance against each criterion. This section shows how to formulate a framework to determine optimal performance measures for each objective ~~i~~ $i \in (1, \ldots, m)$ under uncertain SSP scenarios ~~, where~~ $k \in (1, \ldots, p)$. We describe these performance measures as objective functions representing multiple dimension preferences. Hence, each objective function (meta-criterion) corresponds to preferences pertaining to a criterion in light of an SSP scenario.

The model involves multiple conflicting objectives, and scenarios are employed as possible future states to address deep uncertainty. The model developed here examines the performance of all m criteria under the constraints of all p scenarios in a multi-objective optimization approach. In the context of the concept of meta-criteria analysis, we explored the aggregation of decisions (X_0) that provided the best performance measure across all $m \times p$ meta-criteria (Miettinen, 2012; Ide and Schöbel, 2016). Our study considered the same number of k objective functions for each SSP scenario (p) (See section 3.3.1) with the same meaning, as they must be optimized in the same way.

Our paper presents a study of a multi-scenario multi-objective problem, with $m \geq 2$ objective functions and $p \geq 2$ scenarios, and the problem is defined as follows (Deb et al., 2015):

$$\text{Minimize } \{f_{1k}(x), \ldots, f_{ik}(x)\} \quad k \in \emptyset = \{1, \ldots, P\} \qquad (1)$$
$$s.t. \; x \in P \subseteq \mathbb{R}^n$$

where P are the possible scenarios ~~that each scenario comprises~~ m objective functions ~~and together they create the scenario space $\emptyset$.~~ $X = (x_0, x_1, \ldots, x_{T-1})$ is a vector of decision variables, and T is the planning time frame. f_{ik} is the objective function $i = (1, \ldots, 4)$ for SSP scenario k ~~in the entire scenario space $\emptyset$.~~ f_{ik} $(i = 1, \ldots, m)$ describes objective functions in the scenario $k \in (1, \ldots, p)$. $X = (x_1, \ldots, x_k)^T$ is a vector consisting of k decision variables in the solution domain P of the decision space

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$\mathbb{R}^n$ ($P \subseteq \mathbb{R}^n$). A decision vector $x^* \in P$ is considered Pareto optimum in scenario k if, for at least one index j, there would not occur another $x \in P$ such that for any $f_{ik}(x) \leq f_{ik}(x^*)$ and $f_{jk}(x) \leq f_{jk}(x^*)$. The purpose of the model is to determine a decision vector X that is feasible within all scenarios P and in which no other feasible decision vectors exist for a given scenario k with a better value in one objective function m without requiring the loss of a different objective function (Deb et al., 2015; Shavazipour et al., 2021).

3.3.1 Objective functions

Our proposed framework for adaptation planning was illustrated with a real-world human-water system characterized by diverse socio-economic and environmental conditions, as well as multiple stakeholder groups involved in the human-water system. This presented a great opportunity to evaluate and examine the efficacy of the proposed framework. To develop the model, the system contained multiple conflicting objectives that had to be balanced in problem solving. The objective functions were carefully determined during the previous participatory phase of the project (Inam et al., 2017a,b; Alizadeh et al., 2022a). In the subsequent sections, the primary objective functions featured in the system are described.

3.3.1.1 Farm income function

In the Rechna Doab region, agriculture is the principal source of income, and the aim is to expand agriculture by increasing cropping intensity per unit area, which will increase economic profit and farm income. Therefore, maximization of farm income is considered the primary objective. The seasonal net profit is estimated using the difference between farm expenditures (E) and revenue (R) to determine the net income:

$$f_1(x) = \max\left(\sum_{s=1}^{i} \sum_{p=1}^{j} (R_p^s - E_p^s)\right) \quad (2)$$

$$R_p^s = \sum_{i=1}^{I} (P_i \times Y_p^i \times A_p^i) \quad (3)$$

$$Y_p^i = f_c\left(Ym_i^p \times \alpha W_i \times \beta S_i\right) \quad (4)$$

Subject to:

$$Y_p^i \leq Ym_i^p$$

R_p^s represents the total revenue (\$season-1) and E_p^s represents the total expenses (\$season-1) for each crop in each season. P_i is the market price for crop i (\$ kg^{-1}). ~~Ym_i^p~~ is the actual yield of crop i (kg season^{-1} m^{-2}) and is a function of water stress (W_i) and salinity (S_i). A_p^i is the cultivated area of crop i based on the crop density in the region. Ym_i^p is the maximum yield expected when a crop is not experiencing water or salt stress (kg season^{-1} m^{-2}). α and β (dimensionless) represent the percentage reductions in maximum crop yield owing to water and salinity stress, respectively (Inam et al., 2017a). f_c is the farm economic submodule in the ISESD model that calculates farm income based on net crop yield, crop intensity, agricultural area, prices, soil salinity, and water stress variables.

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3.3.1.2 Groundwater depletion function

Regional authorities have attempted to regulate and manage water resources by limiting or prohibiting the pumping of aquifers to reduce groundwater depletion levels. Therefore, minimizing groundwater drawdowns during the planning period is regarded as an additional conflicting objective and is incorporated as follows into the multi-objective optimization problem:

$$f_2(x) = \min\left(\sum_{s=1}^{i}\sum_{p=1}^{j} {H_d}_p^s\right) \quad (5)$$

$$H_d = f_g\left(T^{p,s}, Q^{p,s}, H_0^p, R^{r,s}, k^p, S_y^p\right) \quad (6)$$

Subject to:

$$H_d \leq \widehat{H_d}$$

where H_d is groundwater drawdown level (m), T denotes the tubewell expansion in polygon p. (number season^{-1}), Q is total aquifer discharge (m^3 d^{-1}), H_0 represents the initial depth of the groundwater table (m), R represents recharge to the aquifer system (m^3 d^{-1}), k is hydraulic conductivity, S_y is specific yield, and $\widehat{H_d}$ represents the maximum permissible drawdown for the aquifer (m). f_g is a submodule of the ISESD model that computes the depth of the groundwater table in the aquifer system using the specified variables.

3.3.1.3 Soil salinity function

The region is severely impacted by soil salinity, resulting in substantial agricultural income losses and environmental damage. Several factors have led to this problem, including inadequate drainage posing challenges with the collection and disposal/reuse of drainage water with salinity levels higher than those of the applied irrigation water, waterlogging, high salinity of irrigation water, and increased evapotranspiration caused by climate change. The electrical conductivity (EC) of the soil is used as a quality indicator to assess its salinity. The objective function of soil salinity is determined by the minimization of EC to meet quality criteria, as shown below:

$$(x) = min\left(\sum_{s=1}^{i}\sum_{p=1}^{j} EC_p^s\right) \quad (7)$$

$$EC_p^s = f_e(EC_0^r, T^{p,s}, Q^{p,s}, H_0^p, R^{r,s}, k^p) \quad (8)$$

Subject to:

$$EC \leq \widehat{EC}$$

where EC_0 is initial salt concentration (dS m^{-1}) and $\widehat{EC}$ is the maximum electrical conductivity threshold allowed (dS m^{-1}). In addition, f_e is a submodule of the ISESD model that simulates salinity concentration in the groundwater and root zone area in the soil.

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3.3.1.4 Policy's reliability function

The human-water system of the Rechna Doab region is unsustainable because the key quantity and quality thresholds of soil salinity and groundwater depletion are exceeded, leading to persistent environmental damage. Therefore, the reliability objective is meant to determine whether the policies are consistent with remaining below these thresholds based on prior studies (Hadka et al., 2015; Quinn et al., 2017). The goal of decision makers is to maximize the average percentage of time the system remains below these thresholds over the planning time horizon. According to this objective function, we seek to maximize the number of times that the amounts of soil salinity and groundwater depletion fall below the critical thresholds of the system (Hadka et al., 2015; Eker and Kwakkel, 2018):

$$f_4(x) = min\left(\frac{1}{sp}\sum_{s=1}^{i}\sum_{p=1}^{j}\delta\right) \; where \; \delta = \begin{cases} 1, & (H_d \leq \widehat{H_d} \wedge EC \leq \widehat{EC}) \\ 0, & (H_d \geq \widehat{H_d} \wedge EC \geq \widehat{EC}) \end{cases} \quad (9)$$

Increasing system reliability involves ensuring that ($\widehat{EC}$) and ($\widehat{H_d}$) thresholds are not exceeded as often as possible (k times out of entire n simulations). An index of the reliability of 1 means that the salinity and groundwater table are below ($\widehat{EC}$) and ($\widehat{H_d}$) thresholds, respectively, and 0 otherwise.

3.3.2 Multi-scenario inter-temporal open-loop solution strategy

The optimization problem is solved using the well-known open-loop intertemporal solution approach (Ward et al., 2015; Hadka et al., 2015; Quinn et al., 2017; Eker and Kwakkel, 2018) in a multi-scenario form. The optimization formulation for the proposed problem includes multi-scenario inter-temporal open-loop control as follows (Deb et al., 2015):

$$F_t(\overline{x}) = \min\{-f_{1p}(x), f_{2p}(x), f_{3p}(x), -f_{4p}(x)\} \quad p \in \emptyset \quad (10)$$

$$s.t. \quad Y_p^i \leq Ym_i^p, H_d \leq \widehat{H_d}, EC \leq \widehat{EC}$$

3.4 Robust Policy Analysis

To explore robust policies, we linked our multi-scenario multi-objective robust optimization framework with our integrated system dynamic model (ISESD) to create an integrated dynamic simulation-optimization model that simultaneously examined multiple objectives in different SSP scenarios. In the search space of the proposed method, all created solutions were robust-efficient across all determined scenarios, thereby enhancing robustness and decreasing scenario dependency. Figure. 3 illustrates the flowchart of the proposed framework for robustness policy analysis. We defined four iterative steps that incorporated various decision analytical methods based on a multi-scenario form of robust multi-objective decision making (Eker and Kwakkel, 2018; Shavazipour et al., 2021) as follows:

i) **Problem formulation:** Identification of the aspects of the problem, such as the decisions, evaluation criteria, uncertain parameters, dynamic interactions, performance measurements, optimization objective functions in of the optimization problem, problem constraints, etc.

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ii) **Identify candidate solutions**: Using multi-objective evolutionary algorithms (Coello et al., 2007; Reed et al., 2013), candidate solutions are identified by solving the problem (Eq.10), which examines multiple objectives and scenarios in a single optimization problem.

iii) **Robustness and deep uncertainty trade-off analysis**: To evaluate the robustness trade-offs among multiple objectives for each candidate solution across SSP scenarios, an ensemble of scenarios is established to investigate the implications of deep uncertainty. Next, solutions are re-evaluated against a broader variety of possible scenarios to assess how robust they are and explore how deep uncertainty affects them.

iv) **Scenario discovery**: The use of scenario discovery techniques allows for the discovery of regions of the uncertainty space ($\emptyset$) where various potential solutions fail to perform. For this purpose, various methods have been developed in the literature. The Patient Rule Induction Method (PRIM) (Friedman & Fisher, 1999) is used to determine the vulnerability, *i.e.*, the combination of uncertainties that result in poor performance by the candidate solutions. PRIM is the most widely used scenario discovery analysis algorithm (Bryant and Lempert, 2010; Lempert, 2013; Kwakkel and Jaxa-Rozen, 2016). It seeks combinations of input factors that give outcomes with similar characteristic values. We used PRIM to gain a better understanding of the integrated dynamic model's results for Rechna Doab.

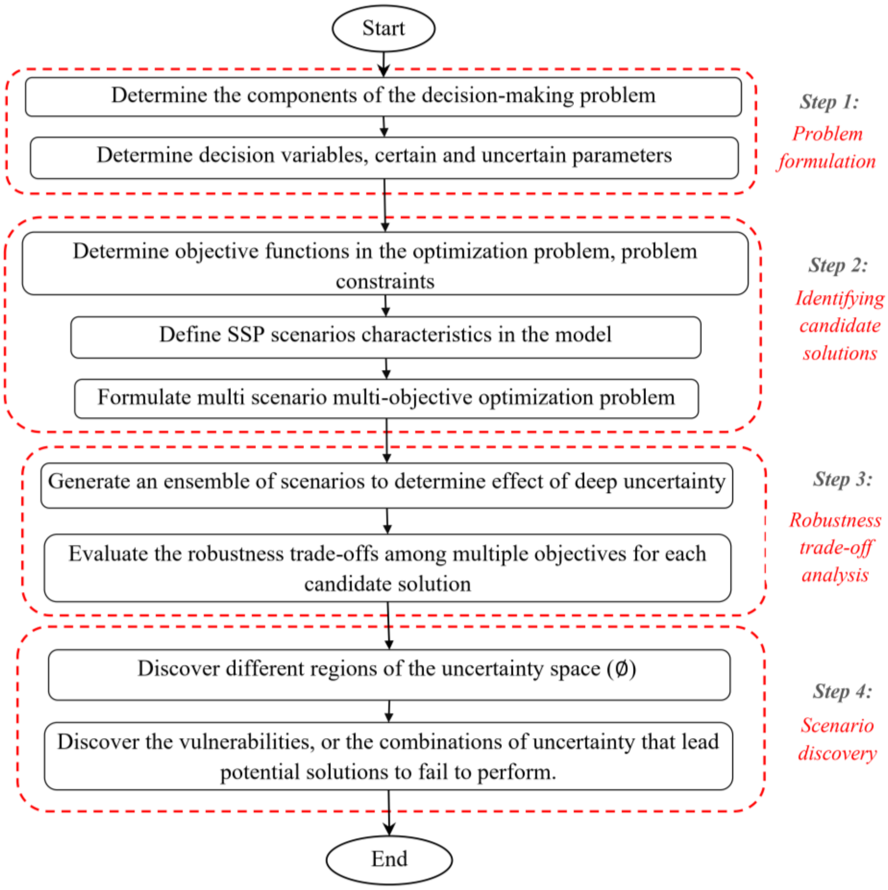

Figure 3: Flowchart of the proposed framework for robustness policy analysis in the multi-scenario multi-objective optimization approach

3.4.1 Robustness measurement

To analyse robustness trade-offs between objectives, the mean/standard deviation measure (Hamarat et al., 2014; Kwakkel et al., 2016) is used. Tied to using index mean/standard deviation is the concept of achieving an accurate average with the minimum deviation possible. The following is the mathematical form of this mean/standard deviation, based on the signal-to-noise ratio in control theory (Eker and Kwakkel, 2018):

$$R_{ij} = \begin{cases} \frac{\mu\left(f_{ijp}^{*}\right)+1}{\sigma\left(f_{ijp}^{*}\right)+1}, & \Leftrightarrow \ f_i \ to \ be \ maximized, \ \ p=(1,\dots,N) \\ \left(\mu\left(f_{ijp}^{*}\right)+1\right)\times\delta\left(f_{ijp}^{*}\right)+1, & \Leftrightarrow \ f_i \ to \ be \ minimized, \ \ p=(1,\dots,N) \end{cases} \quad (11)$$

When candidate solution j is implemented, $\mu\left(f_{ijp}^{*}\right)$ is the outcome scenarios' mean for indicator f_i, and $\sigma\left(f_{ijp}^{*}\right)$ is the standard deviation.

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4 Results

4.1 Trade-offs in a variety of SSP contexts

Depending on the local socio-economic and environmental drivers that triggered robust policy making vulnerabilities, five downscaled SSP scenarios were presented that corresponded to the baseline settings of the system in Rechna Doab in 2020. Under these five different localized SSP scenarios, we examined an optimization problem under multi-scenario multi-objective conditions to design water resources extraction policy portfolios, where each portfolio had four conflicting objectives as defined in Eqs. 2-8. Considering the high dimensions of the problem of the study, the results are presented using parallel plots, as is prevalent in the multi-objective robust optimization literature. Moreover, results are standardized to the interval [0,1] to facilitate ~~more accurate~~ comparisons. In Figure. 4a, multi-objective trade-off configurations for each SSP scenario are shown. Each sphere represents an individual portfolio of solutions. Performance metrics are represented by the spatial coordinates, direction, and size of the sphere, while SSP scenarios are represented by colours. Increasing preference is indicated by the ~~arrow pointed at the~~ graph's axes. In general, the SSP scenario solutions display a variety of trade-offs, with SSP3 and SSP2 exhibiting the most notable variations. SSP1 and SSP5, with systems that are environmentally friendly and efficient, result in more reliable and efficient solutions. Stronger environmental policies, economic growth, and changes in environmental conditions make SSP1 solutions more reliable. However, with groundwater depletion and soil salinity and a greater number of losses, scenarios SSP3, SSP2, and SSP4 are made up of solutions that, on average, would lead to greater environmental degradation than SSP1 or SSP5. Scenario SSP3 portfolios perform the worst in terms of farm income and environmental degradation metrics due to unsustainable water consumption. In this scenario, there is a high demand for local water resources resulting in increased groundwater depletion due to delayed technological advancements, posing more mitigation and adaptation issues.

To understand the differences in outcomes among the five SSP scenarios, we analysed the patterns of the scenarios' outcome indicators. A plot of parallel coordinates is shown in Figure. 4b, which connects the trade-offs shown in Figure. 4a. This Figure illustrates how decision-making policies for water extraction based on multi-scenario multi-objective optimization are affected by SSP scenario circumstances. Lines represent the extraction portfolio for water resources, with hues indicating the optimal SSP scenario. There are generally lower groundwater depletion and soil salinity values in the SSP1 and SSP5 solutions compared to the others. This suggests that eco-friendly policies and practices, such as the conservation of natural resources, can lead to less environmental damage (*e.g.*, soil salinity and groundwater depletion) under the conditions of these SSPs. Within the SSP3 scenario, the solutions contain decision values that result in severe environmental degradation, like the dark pink line in the graph indicating extremely high soil salinity.

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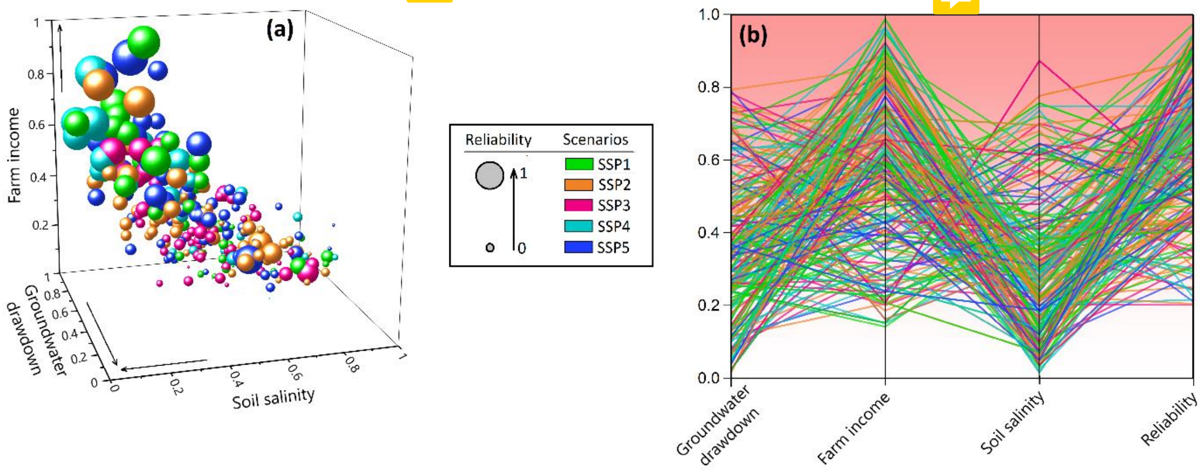
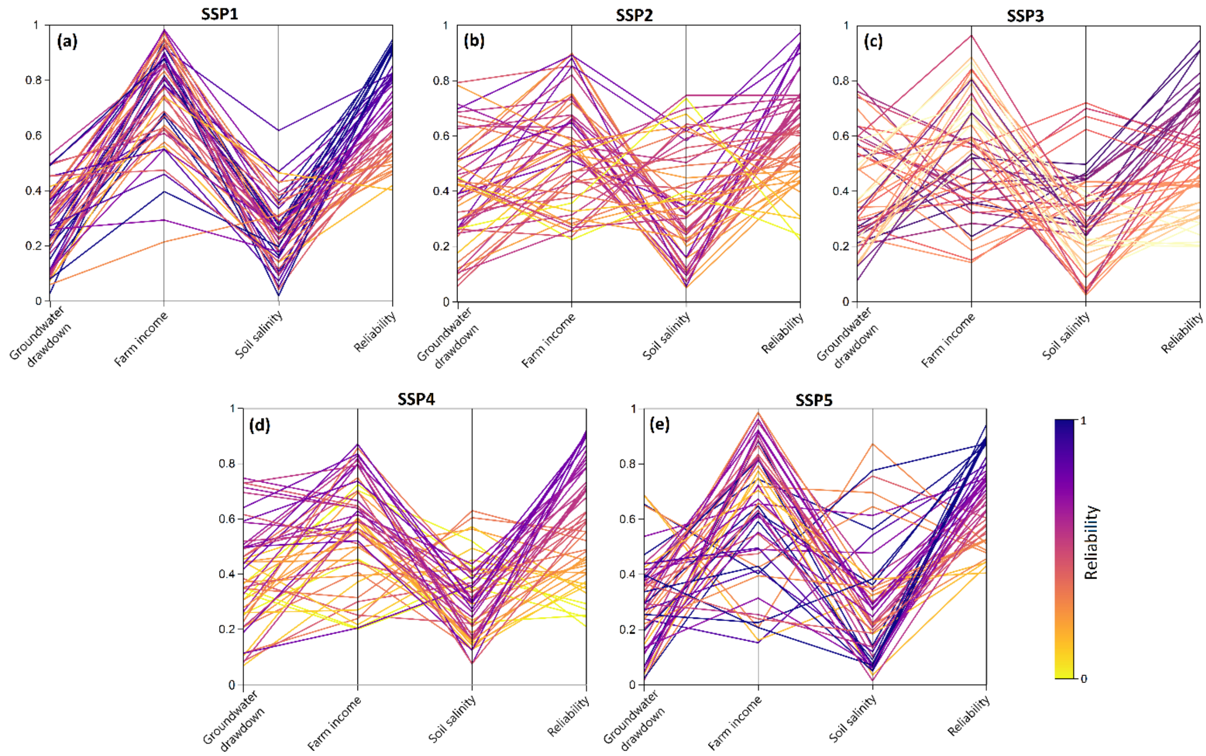


375 **Figure 4: The optimal trade-offs under each of the SSP scenarios: (a) Three-dimensional glyph plot demonstrating non-dominant trade-offs and (b) Parallel graph displaying indicators of non-dominated trade-offs and optimum solutions.**

Figure. 5 shows the performance of Pareto optimum solutions for all four objectives in each of the five SSP scenarios. The colour bar represents the reliability performance of the solutions. The darker the purple, the greater the reliability. As depicted
380 in the Figure, a decrease in reliability is associated with groundwater depletion and increased soil salinity in most SSP scenarios. However, the reverse is evident for systems with higher reliability values, which emphasizes the trade-off between soil salinity, groundwater depletion, farm income, and reliability of performance. In addition, in many scenarios there is a substantial trade-off across scenarios for each objective, particularly in the case of SSP5 and SSP1.



385 **Figure 5: Comparing potential solutions to all four objectives in five SSP scenarios.**

4.2 Robustness analysis

We examined the robustness of the candidate solutions generated by the five SSP scenarios under deep uncertainty. To re-evaluate the candidate solutions and assess their robustness, we constructed 500 randomly selected experimental scenarios using Latin Hypercube Sampling. This was achieved by evaluating the performance of each proposed solution in various
390 scenarios. Each candidate solution was modelled using 500 experimental scenarios by sampling the seven deep uncertainties indicated in Table 2. Using five SSP scenarios, we evaluated the robustness of the candidate solutions against deep uncertainty. A mean-standard deviation measurement based on the ensemble of 500 situations was used to determine whether a potential solution was robust. Based on the means-standard deviation metric, Figure. 6a illustrates robustness trade-offs among the candidate solutions. Lines indicate the robustness of each potential policy solution, and colours indicate their performance in
395 terms of robustness of reliability. In numerous SSP situations, the candidate solutions led to a wide range of robustness trade-offs. When it comes to farm income and reliability, higher normalized mean-standard deviation values are preferred, but lower values are preferred for groundwater depletion and soil salinity. Also, conflicts between the robustness values in conflicting objectives such as increasing farm income and reliability (objectives to be maximized) and reducing groundwater drawdown and soil salinity (objectives to be minimized), can be clearly seen when lines intersect between the columns representing the
400 robustness trade-offs between these four objectives. There are some candidate solutions that exhibit higher favourable

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robustness values in all SSP situations. As part of Figure. 6b, a solution is highlighted that illustrates interesting compromises between performance metrics, shown in bold on top of all the transparent solutions.

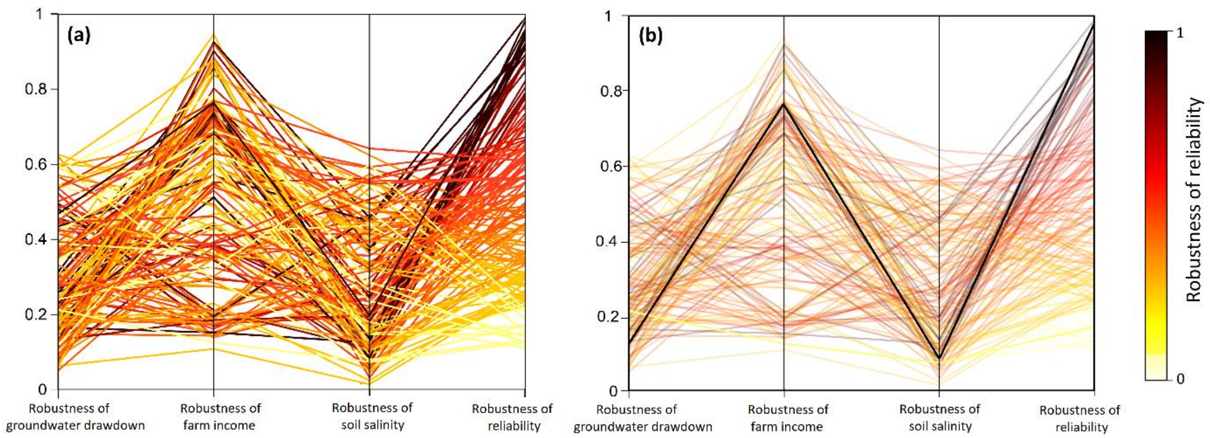

Figure 6: Analysis of robustness trade-offs with normalized mean-standard deviation metric

405 **4.3 Scenario discovery**

A comprehensive examination of the possible region of vulnerability for each objective over a set of generated computational experiments facilitates interpretation of the interaction of deeply uncertain variables in conjunction with one another within the human-water system under consideration. By finding scenarios within some extreme regions of the uncertainty space, we gained a deeper understanding of how systems behave within these regions. This allowed us to obtain a deeper understanding of the system and, if necessary, to adjust the model or our preferences before selecting solutions, thus saving time and effort. Figure. 7 illustrates the interaction between several deeply uncertain variables (see Table 2) that led to weak performance for the ensemble of 500 created experiments during scenario discovery. Precipitation amounts less than 0.06 and temperature changes greater than 0.3 were the most common factors associated with failure. As a result, when higher crop intensities (>0.5) and decreased irrigation efficiency (<0.6) were considered as substantial socio-economic uncertain drivers, the ensemble of created scenarios performed poorly. The effect of additional unclear variables was also evident. For instance, higher values of irrigated area growth could also lead to a loss in reliability, even for lower rates of climatic drivers. In general, we saw a higher failure rate to meet the reliability target in the worst-case combination of socio-economic and climate risks, giving the decision maker a different view of the problem.

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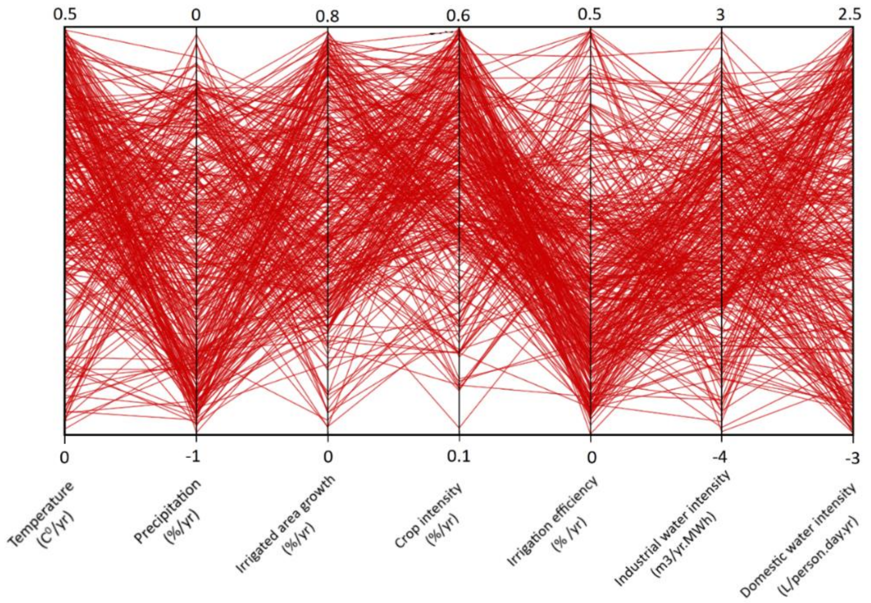

420 **Figure 7: Configurations of uncertain variables values lead to reliability failure.**

The model-provided division is used along with the scenario discovery technique to determine the final set of candidate scenarios. Figure. 8 shows the defining characteristics of these situations as a series of boxplots comparing the range of variables encountered in each SSP scenario. All the uncertain variables and outcomes are divided into these scenarios as a thorough division of all simulations of the model.

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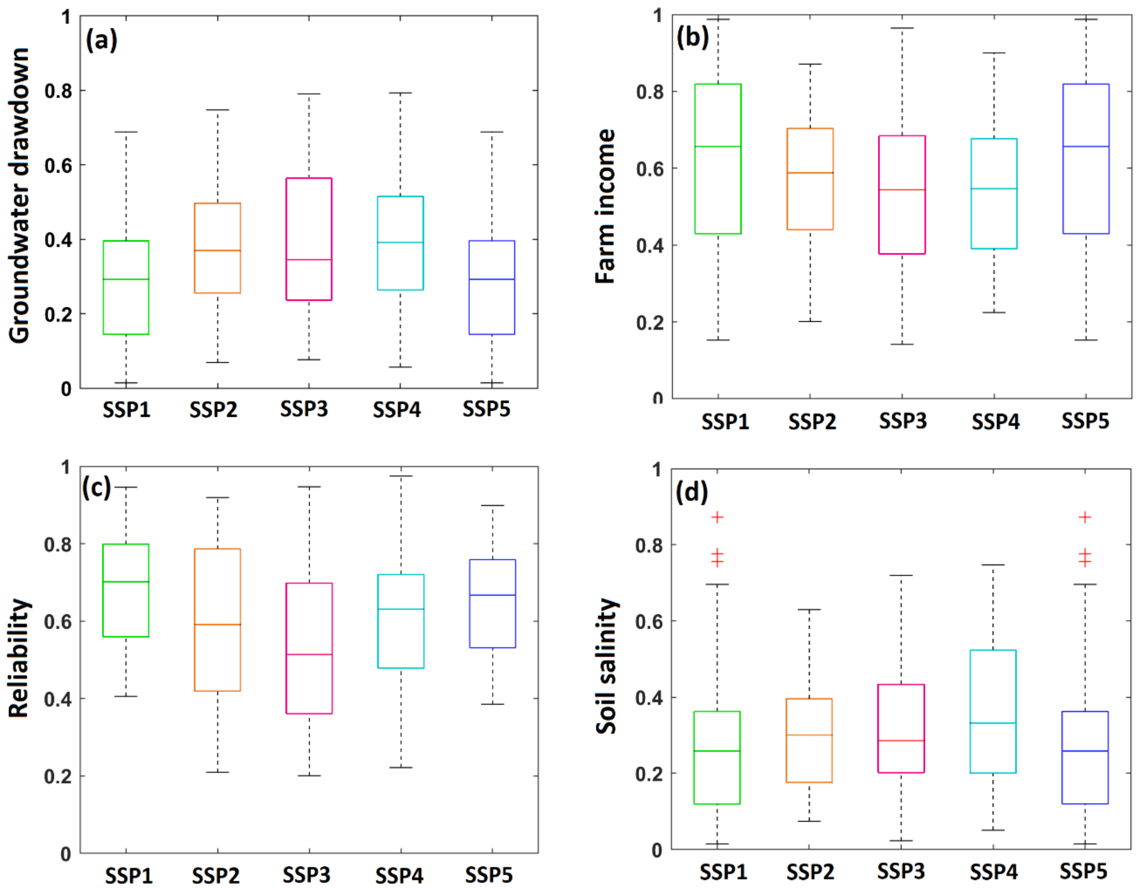

Figure 8: Distribution of model's outcomes based on the final discovered scenarios for the five SSPs.

Figure. 8 shows that systems with more long-term improvement and greater adaptability (*e.g.*, SSP1 and SSP5), provide a higher farm income than other storylines. Both scenarios also exhibit highly successful system reliability (Figure.8c). By examining the impact of stronger environmental measures and varying levels of technological advancement in the agricultural sector together, these two scenarios offered the opportunity to explore policy effectiveness. This could lead to a considerable reduction in environmental degradation by the end of the century. In scenarios SSP2, SSP3, and SSP4, the combination of low farm income (Figure. 8b) and varying levels of reliability (Figure. 8c) result in decreased adaptive capacity due to high consumption and moderate technical development. Of the five scenarios, scenario SSP3 had the lowest farm income, the lowest level of reliability, and the highest intensity of environmental degradation due to its overall lack of technological advancement, lack of robust infrastructure and technology, and inattention to environmental and institutional issues. These scenarios illustrate the prospect that climate policy could result in distinct socio-economic and environmental transformations characterized by substantial improvements in social and economic situations and minimal environmental degradation.

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5 Discussion

Our multi-scenario approach served as the basis for the development of robust policies that would be applicable to a wide range of estimated future world conditions based on certain known downscaled SSP scenarios. Having socio-economic scenarios that are context-dependent for decision making at both the regional and local levels creates an opportunity as well as a challenge for scenario selection (Rosenberg et al., 2014). Based on our results, we can clearly categorize the policy-relevant situations that directly explain the trade-offs between various objectives.

The performance of the various alternatives under a variety of realistic future conditions was evaluated by examining a set of five localized SSP scenarios as part of a model-based evaluation of potential strategic options under deep uncertainty. Each downscaled SSP scenario corresponded to a unique combination of socio-economic and climatic input values (Alizadeh et al., 2022a). However, a variety of methods available for creating these models in complex human-water systems including qualitative participatory methods (Kebede et al., 2018; Lehtonen et al., 2021), purely quantitative approaches incorporating techniques such as scenario development (Guivarch et al., 2016) or decision scaling (Brown et al., 2012; Poff et al., 2016) have been used to analyse SSP scenarios.

Through examining the effect of scenario diversity on the robustness values and ranking of policy alternatives, this study showed that SSP scenarios can be viewed in the context of robust policy making (McPhail et al., 2020). According to our results, the SSP1 scenario had the highest degree of reliability. On the other hand, SSP3 scored the lowest in reliability and exhibited the worst environmental degradation values. The low value for objectives was attributed to the relatively high uncertainty value of socio-economic variables and climate variables associated with the strong need for local resources, the lack of robust infrastructure and technology, and the larger mitigation and adaptation concerns in this scenario (Table 2). According to the SSP scenarios, some solutions could result in undesirable soil salinity, groundwater depletion, and reliability values. However, there were several solutions generated in the SSP1 scenario that resulted in more technological advancements (particularly in the agricultural sector) as well as more improved policies, institutions, and environmental awareness, resulting in favourable values for the objectives. Solutions resulting from scenario SSP5 were very similar to those resulting from SSP1, which was deemed to be the best of the SSP scenarios. With reasonable values for each of the four objectives, the SSP2 scenario was a balanced compromise, and the solutions derived from it demonstrate this same quality. According to the specified SSP situations, the candidate solutions created under SSP3, considered undesirable, were the worst (Figure. 4). This suggested that searching for available alternatives across several SSPs generated a broader range of trade-offs than simply exploring the base-case scenario. A greater variety of candidate solutions within the framework of the proposed approach provided opportunities to rank objectives or agree on acceptable levels of trade-offs (Figure. 5), because one of the goals of the search phase was to inform the robust regional decision-making debate about potentially robust solutions (Knox et al., 2018). As a result, it offered greater insight and options for decision makers. However, it is challenging to establish a direct link between the context in which trade-offs are made and the results of this case study alone. Further local investigations of socio-economic conditions are needed.

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The socio-environmental conditions of an SSP scenario have a significant impact on the computed robustness values (Figure. 6). The interaction of the selected scenario with the collection of SSP scenarios, as well as socio-environmental circumstances of the system performance metric (e.g., adaptability) over the space of probable model input uncertainty, had a significant effect on the robustness values. We evaluated the effects of multiple SSP scenario constraints through scenario discovery and computational experiments, although the results were representative of a wide range of scenarios and robustness metrics, in the case study. In this case, many choices were generated using multiple Pareto fronts. With the generic methodology outlined in this paper, it would be possible to identify if an SSP scenario would provide the same effect if the number of potential options is reduced or consists of a unique Pareto front. Further investigations are needed to comprehend how the number of decision options affects the outcome.

In this study, the combination of the multi-scenario scenario multi-objective robust policy making framework with downscaled SSP storylines from stakeholders allowed for the exploration of a full range of outcomes with associated uncertainties while preserving the integrity of independent candidate scenarios for regional climate change policy making. As a result of our analysis, we were able to observe and investigate the variety of outcomes in SSP scenarios, as well as uncover similar storylines. A variety of possible combinations of outcomes can also be predicted under various SSP scenarios with high or low robustness. The strength of this type of study is that certain situations are likely worth further investigation and that a smaller group of scenarios can be built that encompass a range of possible outcomes. Integrated dynamic modelling of complex human-water systems with a high level of uncertainty and complex interconnections can benefit from this framework. The results showed how a combination of localized SSPs and multi-scenario multi-objective robust analysis could provide novel and important insights for policy formulation and analysis.

In combination with advanced integrated dynamic models and robust policy-making techniques, we demonstrated that downscaled SSP scenarios could be effective for climate adaptation at the regional level, although further research is needed to determine their effect on actual policy-making. Participatory workshops with stakeholders followed by workshops with decision makers can assist in identifying successful policies for long-term adaptation, and the careful examination of the selected solution could be one method of investigating the effects on policy making (van der Pas et al., 2011; Carper et al., 2022).

6 Conclusion

The primary objective of SSP scenario analysis is to provide guidance for the design of adaptation policies with high efficiency for a range of plausible future global conditions. Given that deeply uncertain drivers play a considerable role in determining the relative performance of such robust policies, it is important to use decision-making scenarios that are most relevant to policy considerations and directly explain strategies' trade-offs. This study presents a new framework for integrating multi-scenario analyses of an integrated dynamic model with multi-objective robust policy making concepts to explore downscaled SSP scenarios with stakeholders, suitable for a wide range of climate policy decisions, including mitigation and adaptation. We illustrated how diverse socio-environmental variables of a series of localized SSP scenarios might influence the robustness of policy options in various capacities, demonstrating the applicability of the proposed framework. This study demonstrated that this paradigm facilitates exploring and developing policies for five downscaled SSPs with distinct adaptation and mitigation concerns. An extensive database of multi-scenario scenarios with multiple objective functions may be used to determine which localized SSP scenarios are the most appropriate for an individual characteristic of decision making. Using a real-world human-water system (the Rechna Doab watershed in Pakistan) as a case study and integrating different approaches to creating scenarios used in practice, this study explored how the downscaled SSP scenarios affected the robustness of the system, something that had not been done previously. In cases in which SSP scenario analysis is relevant for analysis, this approach may prove effective. Accordingly, the proposed framework may apply to future developments within the SSP scenarios or in other scenario analyses where there is deep uncertainty surrounding the drivers of future development. This presents a unique opportunity to integrate SSP narrative and quantitative scenario techniques by utilizing quantitative data and analysis to assist in setting a few scenarios and determining the most policy-relevant alternatives to explore.

Data availability

Data used in this study are available by contacting the corresponding author.

Author contributions

Alizadeh M.R.: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Visualization, Writing – original draft. Adamowski, J.: Supervision, Writing – review & editing, Funding acquisition. Qadir M.: Writing – review & editing.

Competing interests

The contact author has declared that neither they nor their co-authors have any competing interests.

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