Development of a Multi-Scenario Multi-Objective Analysis Framework to Explore Optimal, Resilient and Robust Solutions in Coupled Human-Water Systems

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ABSTRACT

Effective management of coupled human-water systems demands resilient-robust policy design, which can help ensure adaptable and flexible policies in highly dynamic, complex, and uncertain contexts. Local and regional human-water systems are bound by variables resulting from the regional context, which are in turn influenced by internal and local constraints connected with particular socio-economic and climatic conditions. However, without a well-defined quantitative framework, developing sustainable policies may be difficult due to the numerous sources of uncertainty and their potential consequences and implications.

To address the complex, multiscale, and uncertain nature of coupled human-water systems, this research develops a novel framework that provides deeper insight into the development of resilient and robust solutions for regional climate change adaptation in the face of deep uncertainty, a situation where an appropriate conceptual model representing the major uncertain drivers, their probability distributions and potential outcomes is unknown. The primary objective of the research is to develop a framework capable of capturing the socio-economic and environmental dynamic interactions of complex human-water systems, as well as policy options that are optimal, resilient, and robust under changing climate and socio-economic conditions. The framework is developed, tested, and applied to evaluate potential policies under a variety of localized Shared Socio-economic Pathways (SSP) scenarios for human-water related vulnerabilities in the Rechna Doab region of Pakistan, which serves as an example of a real-world multi-stakeholder coupled human-water system in a developing country.

The new framework has four fundamental pillars: 1) A localized SSP-RCP scenarios framework is developed using an interdisciplinary and storyline development approach that combines bottom-up local expert-stakeholder knowledge with top-down insights from global SSPs scenarios, 2) A multidisciplinary approach that integrates storytelling and probabilistic approaches is developed to characterize and comprehend uncertainty through linguistic and epistemic uncertainty quantification in the context of a regional integrated dynamic model, 3) An integrated socio-economic and environmental system dynamic model is utilized to evaluate the complex human-water system's dynamic interactions and vulnerabilities, 4) A multi-scenario, multi-objective (meta-criteria) robustness and resiliency optimization model is developed to discover optimal resilient-robust policies that perform efficiently under a set of downscaled SSPs while accounting for deep uncertainty.

The suggested framework proved effective at evaluating the resilience-robustness of the human-water system in the context of various socio-environmental and climatic disturbances. The study demonstrates how the suggested paradigm can provide new information in human-water system evaluations, contributing to the growing support for resiliency-robustness evaluations in the light of deep uncertainty. It offers stakeholders and decision-makers with a deeper understanding of the vulnerabilities and adaptive capacity of individual variables within coupled human-water systems. This analysis improved the quantification and comprehension of uncertainty in integrated assessment modeling of the coupled human-water system and the complex interactions between inputs and outputs. Using localized SSPs, the proposed framework demonstrates how implementing multi-scenario, multi-objective resilient-robust policy-making with dynamically integrated modeling of complex human-water systems can provide useful insights for identifying resilient robust optimal solutions for regional climate change adaptation. The suggested framework supports the development of future adaptation policies that take into account socio-economic and climate change circumstances, as well as regional and local governance.

RÉSUMÉ

Les systèmes homme-eau sont parmi les systèmes contribuant au progrès de la société. Une gestion efficace des systèmes couplés homme-eau nécessite une élaboration de politiques resilientes-robustes, assurant des politiques adaptables and flexibles dans des contextes extrèmement dynamiques, complexes, et incertains. Les systèmes homme-eau locaux et régionaux sont délimités par des variables liées au contexte régional, qui sont, à leur tour, influencés par les politiques internes liées aux conditions socio-économiques and climatiques particulières. Cependant, sans un cadre quantitatif bien défini, le développement de politiques durables peut s'avérer difficile étant donné les multiples sources d'incertitude, et leurs conséquences et ramifications potentielles.

Afin de s'adresser à la nature complexe, multi-échelle, et incertaine des systèmes couplés homme-eau, la présente recherche élabora un cadre novateur offrant un aperçu approfondie de l'élaboration de solutions résilientes-robustes pour l'adaptation aux changement climatiques régionaux dans une situation de profonde incertitude. Le principal objectif de la recherche fut d'élaborer un cadre pouvant saisir les interactions dynamiques socio-economiques et environnementales de systèmes homme-eau complexes, et d'identifier les options politiques optimales, résilientes et robustes face à des conditions climatiques et socio-economiques en évolution. Le cadre fut élaboré, mis à l'épreuve, puis utilisé pour évaluer une gamme de politiques sous différentes trajectoires socio-économiques partagées (TSP) s'adressant aux vulnérabilités liées aux systèmes homme-eau dans la région Rechna Doab du Pakistan. Cela servit comme exemple en vie réelle d'un système couplé homme-eau dans un pays en voie de développement.

Le nouveau cadre s'appuie sur quatre piliers: (*i*) un cadre localisé de trajectoires socio-économiques partagées/représentatives de concentration fut élaboré grâce à une approche de développement de scénario interdisciplinaire du bas vers le haut combinant les connaissances des experts-parties prenantes et des perspective de haut en bas provenant de scenarios TSP, (*ii*) une approche multidisciplinaire intégrant les narratifs and des approches probabilistiques fut élaborée afin de caractériser et comprendre l'incertitude par une quantification linguistique et épistémique de l'incertitude dans le contexte d'un modèle dynamique régional intégré, (*iii*) un système dynamique de modèle socioéconomique and environnemental servit à évaluer les interactions dynamiques et vulnérabilités d'un système homme-eau complexe , (*iv*) un modèle d'optimisation multi-scenario, multi-objectif (méta-critères) de la robustesse et de la résilience fut élaboré afin d'identifier les politiques résilientes/robustes opérant de façon efficace sous un ensemble de TSP

à échelle réduite, tout en prenant compte d'une profonde incertitude.

Le cadre proposé s'avéra très efficace dans l'évaluation de la résilience-robustesse du système homme-eau dans le contexte de diverses perturbations socio-environnementales et climatiques. Cette étude démontra que le paradigme ci-évolué peut fournir des informations supplémentaires dans l'évaluation des systèmes homme-eau, contribuant ainsi à un soutien croissant pour les évaluations de la resilience/robustesse, lorsqu'on fait face à une incertitude profonde. Il offre aux intervenants et décideurs une compréhension plus approfondie des vulnerabilités et de la capacité d'adaptation des variables individuels dans les systèmes couplés homme-eau et des interactions complexes entre entrées et sorties. Utilisant des TSP localisées, le cadre préconisé démontre comment l'élaboration multi-scénario, multi-objectif et résiliente-robuste des politiques avec une modélisation dynamique intégrée de systèmes homme-eau peut fournir des aperçus pouvant server à identifier des solutions résilientes-robustes pour les politiques régionales d'adaptation au changement climatique. Le cadre suggéré soutien le développement de politiques d'adaptation qui tiennent compte des circonstances socioeconomiques et du changement climatique, ainsi que la gouvernance régionale et locale.

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FORMAT OF THE THESIS

This thesis is submitted in the format of papers suitable for journal publication. This thesis format has been approved by the Faculty of Graduate and Postdoctoral Studies, McGill University, and follows the conditions outlined in the Guidelines Concerning Thesis Preparation, which are as follows:

“As an alternative to the traditional thesis format, the dissertation can consist of a collection of papers of which the student is an author or co-author. These papers must have a cohesive, unitary character making them a report of a single program of research. The structure for the manuscript-based thesis must conform to the following:

Candidates have the option of including, as part of the thesis, the text of one or more papers submitted, or to be submitted, for publication, or the clearly-duplicated text (not the reprints) of one or more published papers. These texts must conform to the "Guidelines for Thesis Preparation" with respect to font size, line spacing and margin sizes and must be bound together as an integral part of the thesis. (Reprints of published papers can be included in the appendices at the end of the thesis.)

The thesis must be more than a collection of manuscripts. All components must be integrated into a cohesive unit with a logical progression from one chapter to the next. In order to ensure that the thesis has continuity, connecting texts that provide logical bridges between the different papers are mandatory.

The thesis must conform to all other requirements of the "Guidelines for Thesis Preparation" in addition to the manuscripts.

The thesis must include the following:

(a) A table of contents;
(b) An abstract in English and French;
(c) An introduction which clearly states the rational and objectives of the research;
(d) A comprehensive review of the literature (in addition to that covered in the introduction to each paper);
(e) A final conclusion and summary;

1. As manuscripts for publication are frequently very concise documents, where appropriate, additional material must be provided (e.g. in appendices) in sufficient detail to allow a clear and precise judgment to be made of the importance and originality of the research reported in the thesis.
2. In general, when co-authored papers are included in a thesis the candidate must have made a substantial contribution to all papers included in the thesis. In addition, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. This statement should appear in a single section entitled "Contributions of Authors" as a preface to the thesis. The supervisor must attest to the accuracy of this statement at the doctoral oral defense. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to clearly specify the responsibilities of all the authors of the “coauthored papers”.

CONTRIBUTIONS OF AUTHORS

The third through sixth chapters of this dissertation have been published, submitted for publication, and presented at numerous scientific conferences. The author of this dissertation was responsible for the development, testing, and application of the various methods discussed in this research, as well as the preparation of manuscripts submitted to peer-reviewed journals and oral and poster presentations presented at scientific conferences. Prof. Adamowski is the supervisor for this thesis and contributed to the review and editing of each publication, poster, and oral presentation, in addition to providing valuable advice on all aspects of the research.

Dr. Azhar Inam, Assistant Professor in the Department of Agricultural Engineering at Bahauddin Zakariya University in Pakistan, helped with data collocation and contributed to the review and editing of the first and second manuscript published in the journal of Science of the Total Environment and Journal of Hydrology. Dr. Manzoor Qadir, Professor in the United Nations University Institute for Water, Environment and Health (UNU-INWEH), contributed to the review and editing of the third manuscript submitted for publication in Hydrology and Earth System Sciences. Dr. Mojtaba Sadegh, Assistant Professor of Civil Engineering at Boise State University and Dr. Ali Mehran, Assistant Professor of Earth and Geospatial Science at University of North Georgia contributed to the review and editing of the fourth manuscript submitted for publication in Water Resources Research.

List of publications and scientific presentations related to the thesis:

A. Part of this thesis has been published/submitted as follows;

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Alizadeh, M.R., Adamowski, J. and Inam, A., 2022. Scenario analysis of local storylines to represent uncertainty in complex human-water systems. Journal of Hydrology (Under review).

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Alizadeh, M.R., Adamowski, J. and Sadegh, M., Mehran, A., 2022. Resilient-robust policy design for coupled human-water systems: Insights form integrated dynamic modeling. Journal of Water Resources Research (Under review).

B. Part of this thesis has been presented at scientific conferences;

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Alizadeh M.R., Adamowski J.F., 2022, Multi-scale scenarios for local climate change policies, EGU General Assembly 2022, EGU22-9025.

Alizadeh M.R., Adamowski J., 2021, Confronting Deep Uncertainty in Coupled Socio-economic and Environmental Models for Robust Decision Making, 1st Sociohydrology Conference, Sept. 2021, Delft University, Netherlands.

Alizadeh M.R., Adamowski J., Inam A., 2021, Participatory Management of Water Resources under Climate Change: Assessing Coupled Human-Water Systems, American Society of Agricultural and Biological Engineers (ASABE), Michigan, USA.

Alizadeh M.R., Adamowski J., Inam A., 2020, Integrating Storytelling and a Coupled Socio-Hydrological Model to Explore Interactions, Uncertainties and Vulnerabilities of Complex Human-Water Systems, AGU2020.

Alizadeh M.R., Adamowski J., Malard J., Inam A., 2020, Participatory-Exploratory Modeling of Coupled Socio-Economic and Environmental Systems for Adaptive Management of Water Resources, EGU2020.

Alizadeh M.R., Adamowski J., 2020, Exploring interactions, uncertainties, and vulnerabilities of complex social-environmental systems using integrated socio-economic and environmental models, CentrEau Student Day (JQEC), Polytechnique Montréal (Selected talk).

Alizadeh M.R., Adamowski J., Azhar I., Malard M., 2019, Participatory dynamic adaptive policy-making for sustainable environmental and water resources management. NABEC 2019, Quebec City, Canada.

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LIST OF ABBREVIATIONS

BCM	Billion Cubic Meters
CART	Classification and Regression Trees
CHW	Coupled Human-Water
CLD	Causal Loop Diagram
CoG	Center of Gravity
DLR	Directorate of Land Reclamation
GB-PSDM	Group Built Physical System Dynamics Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information Systems
ISESD	Integrated Socio-Economic and Environmental System Dynamic
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
LSSP	localized Shared Socio-economic Pathway
MORDM	Multi-Objective Robust Decision Making
MORO	Multi-Objective Robust Optimization
NGOs	Non-Governmental Organization
P-GBSDM	Physical-Group-Built System Dynamics Model
PID	Punjab Irrigation Department
PMD	Pakistan Meteorological Department
PRIM	Patient Rule Induction Method
Rci	Corrective Impact
RCP	Representative Concentration Pathway
Rd	Degree of Return
Rp	Post-Disturbance Perturbation
Rr	Rate of Return
Rt	Recovery
SAHYSMOD	Spatial Agro Hydro Soil Salinity and Groundwater Model
SMO	Soil Monitoring Organization

SSP	Shared Socio-economic Pathway
SSP-RCP	Shared Socio-economic Pathway - Representative Concentration Pathway
WAPDA	Water and Power Development Authority
WASID	Water and Soil Investigating Division

CHAPTER 1: **Introduction**

Changes in social, economic, and natural environments pose a growing threat to the viability of current environmental and water resources management structures. A combination of technological advances, socio-economic and climate changes, and population growth have changed land cover and water demands. The severity and frequency of extreme events (*e.g*., floods and droughts), are increasing due to changes in precipitation and temperature patterns. Climate change and socio-economic factors will likely affect the quantity and quality of water resources available in the future. A lack of appropriate adaptation or planning for these changes will put many people at risk of water-related problems (*e.g*., water scarcity and flooding), especially in sensitive areas such as developing nations. The management of sustainable water resources in human-water systems therefore requires new frameworks, methods, and strategies.

To ensure sustainable strategies in human-water systems, solutions must be developed that are capable of withstanding unforeseeable changes in the future. Developing resilient and robust solutions to environmental problems is essential even under shifting conditions. However, it is difficult to make informed decisions and formulate effective policies due to complicated interactions between drivers, the high dynamic and intrinsic uncertainties of the future, and increasing demands on the human-water system. The complexity and dynamic interactions between society and the environment, as well as external pressures such as climate change and socio-economic factors (*e.g*., populations growing and economic advancements), lead to severe uncertainty making forecasting climate and socio-economic trends in the future very difficult.

Furthermore, societal changes as well as adaptation policy options will be affected by factors regarding future socio-economic and climatic changes. Understanding how society interacts with the water system is critical to understanding the effects of future uncertainty, and adaptation policies. Sustainability policies should be adaptable and resilient and robust to uncertainty, while meeting economic, environmental, and social objectives. Human-water interaction dynamics and the resilience and robustness of policies are often ignored in current water resource planning, which is based on forecasting future occurrences.

The present research aims to derive new knowledge, providing a clearer insight into the development of methods for resilient-robust policymaking under deep uncertainty for sustainable water resource management in coupled human-water systems. The main goal of the research is to provide a framework that can capture the socio-economic and environmental dynamic interactions of complex human-water systems and provides policy options that are optimal, resilient and robust under deeply uncertain climate and socio-economic conditions in the future.

1.1 Challenge 1: Regional and Local Scales of Socio-economic and Climate Projections

At the local and sub-regional levels, human-water systems are constrained by regional conditions, which, in turn, are affected by constraints associated with particular socio-economic and climatic conditions. This implies that any multi-scale scenario framework must take into account the various scales at which the variety of socio-economic change will occur (*e.g.*, Biggs et al., 2007; Zurek and Henrichs, 2007; Schweizer and Kurniawan, 2016). It is essential, however, to incorporate stakeholder knowledge and concerns when constructing local socio-economic scenarios. To achieve this goal it is essential that major stakeholders participate in a constructive participatory process (Alcamo, 2008; Zscheischler et al., 2018; Allan et al., 2021). The use of regional integrated modeling within the context of participatory modeling is vital to integrating bottom-up studies of local processes into top-down methodologies. Through hybrid top-down and bottom-up approaches across many scales, from global to regional and short-term to long-term, the integration of expert-based and participatory methods facilitates the construction of well-balanced scenarios (van Ruijven et al., 2014). It is also necessary to downscale regional and local climate projections so that they are compatible with expected social trends. When it comes to local impacts that disseminate beyond borders into other socio-economic realms, it is equally challenging to specify consistent future conditions (Challinor et al., 2017). It is therefore necessary to examine and quantify potential future climate and socio-economic combinations at regional and local levels.

1.1.1 Solution to Challenge 1

To address these objectives and constraints, this research developed a hybrid scenario paradigm of Shared Socio-economic Pathways-Representative Concentration Pathways (SSP-RCP) at a localized scale. To this end, the storytelling approach within the context of participatory modeling is employed to elicit the local knowledge and perspectives of stakeholders regarding socio-economic and climate change circumstances in the local system. In addition to climate projections, local narratives are used to estimate risks associated with climate change and socio-economic development. Using global SSPs (SSP1 through SSP5) combined with climate change pathways (RCP4.5 and RCP8.5) as boundary conditions, the study built localized SSP narratives through an iterative, participatory process.

1.2 Challenge 2: Uncertainty in Complex Human-Water Systems

The interactions between human and water systems are intricately interconnected; therefore, any uncertainty within them may be amplified (Dawson et al., 2011; Brown et al., 2015). As a result, there are several ambiguous, complex, and poorly understood connections between human and environmental systems (Sivapalan et al., 2014; Herman et al., 2020). Climate change and socio-economic unpredictability create ambiguity in complex human and environmental systems due to severe uncertainty over degree and impacts (Kasprzyk et al., 2013; Brown et al., 2015; Giuliani et al., 2016; Herman et al., 2020). Defining causal links in complex environmental and socio-economic systems based on deterministic models ignores the ambiguities and variability inherent in causality. A simple cause-and-effect diagram cannot adequately convey the complexity of interconnectedness of such systems in real life. The numerous sources of uncertainty as well as their implications and potential impacts can make the development of sustainable policies difficult without a well-defined quantitative framework.

1.2.1 Solution to Challenge 2

This study proposes a novel framework that combines qualitative storytelling approaches with probability-based simulations of low discrepancy sequences sampling and scenario discovery techniques to characterize and comprehend the uncertainty in significant socio-environmental outcomes in integrated dynamic models. Specifically, this study sheds light on how to evaluate uncertainties and vulnerabilities by employing an efficient participative analysis of storyline narratives under scenario discovery of many feasible future projections. This research demonstrates how narrative storytelling may be used to build probability distributions for uncertain socio-environmental drivers. The study also identifies possible policy-relevant narratives via the merging of narratives and quantitative scenario approaches. The experiences of stakeholders are used to build narratives that illustrate the interdependence of socio-environmental factors in complex human-water systems.

1.3 Challenge 3: Robust Policies in Coupled Human-Water Systems

Policy formulation in complex human-water systems is greatly hampered by deep uncertainty when using downscaled SSP scenarios (Bankes, 2002; Kwakkel et al., 2010; Walker et al., 2012). In recent years, deep uncertainty has expanded to encompass all uncertainties with no precise probability level (Lempert, 2003; Maier et al., 2016). Deep uncertainty occurs when stakeholder groups cannot agree or know what the underlying probabilities are for the major input parameters. Walker et al. (2013) simplifies this by defining "deep" uncertainty as a situation when numerous plausible future options can be listed, but alternatives cannot be ranked based on perceived likelihood. Climate adaptation techniques based on limited scenarios are highly risky, as they may be effective in one but ineffective in another. Future changes in the climate and socio-economic conditions are two significant sources of uncertainty in coupled human-water systems. Due to the extreme unpredictability of the future in terms of social, economic, and environmental issues, it is essential to evaluate policies using several scenarios that span a wide range of potential outcomes (Hallegatte 2009; Lempert 2013). In such complex systems, the concept of robust policy making in coupled human-water systems emerges as an essential component of policy design. A robust policy that is dependable over the planning horizon of the system using conventional methods like optimization problems may fail to take into account the risk associated with profound uncertainty and dynamic interactions.

1.3.1 Solution to Challenge 3

The goal of this research is to support the development of highly effective policies that are adaptive-robust and highly efficient under a variety of realistic scenarios for the future. Given that highly uncertain drivers play a significant role in deciding the relative effectiveness of such robust policies, it is crucial to employ decision-making scenarios that are most pertinent to policy considerations and to explain the trade-offs of strategies in a direct manner. To explore downscaled SSP scenarios with stakeholders, this study develops a new framework that integrates a dynamic simulation-optimization model with multi-objective robust policy-making concepts to explore a wide range of climate policy decisions (*e.g.*, mitigation and adaptation), using an integrated dynamic simulation-optimization model. This research demonstrated the applicability of the proposed approach by illustrating how distinct socio-environmental elements of a series of localized SSP scenarios may influence the robustness of policy options in various capacities. In this study, the localized SSP scenarios are examined to determine how they impacted the robustness of the system in practice.

1.4 Challenge 4: Resilience-Based Robustness in Coupled Human-Water Systems

In coupled human-water systems, resilience is frequently associated with the capacity to attain or maintain sustainable development objectives (Mayer et al., 2014; Carper et al., 2022). Human-water systems that are resilient to climatic change and socio-economic change are more likely to attain and maintain sustainable, functional states (Liu et al., 2007; Alberti et al., 2011; Konar et al., 2019). In response to future changes and shocks, resilience in human-water systems refers to the ability of social systems, such as institutions, governance, and policymaking, to turn perception into collective action (Mao et al., 2017; Xu et al., 2021; Carper et al., 2022). The term emphasizes the importance of society and social conduct in facilitating human adaptation to environmental changes. It allows for the explanation of even more complicated system feedback loops between human and water systems when modeling interactions of coupled human-water systems that contribute to resilience (Xu et al., 2018; Dewulf et al., 2019; Carper et al., 2021). There is a need for studies and frameworks that provide a more comprehensive synthesis of how these concepts relate to resiliency concepts, particularly in the context of deep uncertainty from various plausible futures. Moreover, despite the fact that multiple research efforts have incorporated resilience criteria in human-water systems, none of these studies have used the measurements under the deep uncertainty associated with a vast array of socio-economic and climate changes. In addition, the effectiveness of these approaches in SSP scenario studies has not yet been evaluated. In addition, the majority of research on human-water resilience depends on conceptual frameworks rather than a quantitative investigation of a real-world case study to determine the most effective resilient adaptation policies. The suggested technique assists in analyzing the resilience of policy-making in coupled human-water systems for future developments within SSP scenarios where the drivers of future change are characterized by deep uncertainty.

1.4.1 Solution to Challenge 4

To address this need for exploring resilient and robust solutions in coupled human-water systems, this research presents a multidisciplinary framework for integrating the concepts of multi-scenario multi-objective optimization analysis (meta-criteria analysis) and robustness and resiliency analysis to facilitate the development of adaptation policies that are optimal, robust, and resilient in the face of deep uncertainty associated with localized SSP scenarios in a coupled human-water system. To evaluate potential policies under a variety of localized SSP scenarios, this study incorporates five quantitative resilience metrics as an objective function in a multi-scenario multi-objective optimization process integrated into a robust policy-making framework. By coupling an integrated dynamic simulation model with a multi-scenario multi-objective optimization framework, this study creates an integrated dynamic simulation-optimization model to evaluate potential solutions and their resilience based on five resilience objectives. This research take into account deep uncertainty in the multi-objective optimization search phase of the integrated dynamic simulation-optimization model as we simulate the vulnerabilities of a complex human-water system. The proposed methodology helps to analyze the resilience of policy-making in coupled human-water systems for future developments within SSP scenarios where there is deep uncertainty surrounding the drivers of future changes.

1.5 Research Questions

This research addresses the following sustainability-related questions:

Objective 1:

1. How can integrating top-down and bottom-up approaches help calibrate global scenarios with regional stakeholders' narratives to achieve a balance between local and global perspectives?
2. How can regional integrated models provide a rigorous assessment and quantification of vulnerabilities in coupled human-water systems under localized/downscaled SSP-RCP narratives?

Objective 2:

3. How can we create probability distributions of uncertain socio-environmental drivers in a complex human-water system using narratives from stakeholders?
4. In what ways can an integrated socio-economic and environmental model effectively yield insights into the uncertainties of a complex human-water system?
5. Are there prevalent narratives that demonstrate a significant relationship between some variables of interests (*e.g.*, farm income) and the other outcomes of the integrated dynamic model?

Objective 3:

6. How can we determine robust policy in coupled human-water systems under deep uncertainty of localized SSP scenarios using integrated modeling approaches?

Objective 4:

7. How coupled human-water systems react to disturbances and uncertainties of future SSPs scenarios in the context of resiliency behaviour?
8. How resiliency concepts fit with robust policy design framework, to develop optimal resilient-robust solutions particularly when deep uncertainty from multiple plausible futures is concerned.

1.6 Research Objectives

The main focus of this Ph.D. research is to provide knowledge, tools, and methodologies for exploring the dynamic interactions, deep uncertainty, and vulnerabilities of complex human-water systems to facilitate resilient robust policymaking in sustainable water resources management in coupled human-water systems. In particular, this entails the following four objectives:

Objective 1: Evaluating socio-environment and climate change impacts on vulnerability of the system under the projection of climate change (RCPs) and socio-economic scenarios (SSPs) using an ensemble of localized RCP-SSPs scenarios

- Downscaling shared socio-economic pathways (SSPs) scenarios based on regional narrative storylines

- Linking local stakeholder scenarios and global shared socio-economic pathways (SSPs)
- Projecting water resources conditions by developing an ensemble of shared socio-economic pathways (SSPs) and climate change scenarios (RCPs) framework

Objective 2: Integrating storytelling and probabilistic methods to explore and characterize uncertainties (linguistic and pessimistic uncertainty) of complex human-water systems

- Determining the most influential uncertain drivers and assessing the future of the system using stakeholder-led scenarios through participatory activities
- Characterizing probability distributions of uncertain socio-environmental drivers using storyline narratives
- Scenario discovery analysis serves to explore the relationship between outcomes and discover cohesive storylines of interest

Objective 3: Multi-scenario multi-objective analysis of downscaled shared socio-economic pathways (SSPs) for robust policy development in human-water systems under deep uncertainty

- Identifying optimal policies that function robust under a set of downscaled SSPs by developing an integrated dynamic simulation-optimization model
- linking an integrated dynamic simulation model with a multi-scenario multi-objective optimization framework
- Applying a scenario discovery (SD) method to assess the impact of deep uncertainties

Objective 4: Resilience-based robust policy design for coupled human-water systems

- Incorporating resiliency into a multi-scenario multi-objective robust optimization framework
- Developing optimal trade-offs considering robustness and resilience preferences for sustainable solutions under deep uncertainty

While the first objective is concerned with constructing a set of localized SSP-RCPs scenarios based on the narratives of stakeholders, the second objective is concerned with quantifying the uncertainty of these scenarios. The third objective builds on the first and second objectives and is designed to cater to robust policy design under developed scenarios and uncertainty. The fourth objective extends the novel method introduced in the third objective by incorporating the concept of resilience as an additional crucial aspect of policy formulation in coupled human-water systems to improve candidate solution discovery. The objective of each specific objective is to demonstrate how a multidisciplinary framework based on the integration of social science (in objectives (1) and (2)) and engineering-based approaches can be utilized to develop a framework for resilient-robust policy making under deep uncertainty for coupled human-water systems.

1.7 Contributions

The research contained in this thesis is innovative in four main ways:

Objective 1: Integrating interdisciplinary and participatory storyline development process that integrates bottom-up local expert-stakeholder knowledge with top-down insights from global SSPs to develop a set of localize/downscaled SSPs. It also develops, tests, and applies the first localized RCPs-SSP framework in an integrated dynamic modeling approach to assess vulnerabilities of coupled human-water systems at a regional scale.

Objective 2: It develops, tests, and applies the first qualitative storytelling approaches with probability-based simulations of low discrepancy sequences sampling and scenario discovery methods to characterize and understand the deep uncertainty in important socio-environmental outcomes in integrated dynamic models of coupled human-water systems.

Objective 3: It develops, tests, and applies the first multi-scenario multi-objective optimization robust analysis (meta-criteria analysis) through an integrated system dynamics simulation-optimization model to design different policy options in complex human-water systems under a variety of plausible SSP scenarios. The proposed framework also considers deep uncertainty analysis in the optimization phase of the analyses.

Objective 4: It develops, tests, and applies the first resilience-based robust policy making in coupled human-water systems. It presents a multidisciplinary framework on how the concepts of multi-scenario multi-objective optimization analysis (meta-criteria analysis) of robustness and resiliency analysis, can be integrated together to facilitate the development of adaptation policies that are optimal, robust, and resilient to dealing with deep uncertainty related to localized SSP scenarios in a coupled human-water system.

1.8 Thesis Outline

Existing literature on storytelling methods and localized hybrid Shared Socio-economic Pathway - Representative Concentration Pathway (SSP-RCP) frameworks, deep uncertainty analysis, scenario discovery, multi-scenario multi-objective robust optimization and resilience-based robust policy design in coupled human-water systems are reviewed in Chapter 2. The literature review is followed by four connected manuscripts.

The first manuscript (Chapter 3) discusses integrated assessment modeling of a localized hybrid Shared Socio-economic Pathway - Representative Concentration Pathway (SSP-RCP) framework, through an interdisciplinary and participatory storyline development process that integrates bottom-up local expert-stakeholder knowledge with top-down insights from global SSPs.

The second manuscript (Chapter 4) discusses the framework for representing uncertainty through linguistic and epistemic uncertainty quantification using storyline narratives in the context of a regional integrated dynamic model. A systematic exploration of uncertainty space is presented using storytelling, fuzzy sets, and low discrepancy sequences sampling methods.

The third manuscript (Chapter 5) discusses the new framework that integrates a multi-scenario multi-objective analysis of a set of downscaled SSPs with the robust optimization concept, to find robust optimal solutions under deep uncertainty. The use of the integrated dynamic simulation-optimization model to discover potential policy alternatives is discussed, and the latter's robustness is presented based on four considered objectives.

The fourth manuscript (Chapter 6) discusses a novel resilience-based multi-scenario multi-objective robust optimization framework developed to find optimal resilient-robust solutions under various socio-economic and climate disturbances related to a set of downscaled shared socio-economic pathways (SSP) scenarios. This section highlights the significance of this work and explains how to evaluate potential solutions and their resilience in accordance with five resilience objectives under deep uncertainty.

Chapter 7 discusses the conclusions derived from the most important results of this research.

Chapter 8 recounts the primary contributions of this research to the literature, and indicates several avenues for future research.

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CHAPTER 2: **Literature Review**

The prime focus of this research was to develop a multidisciplinary modeling framework for exploring resilient-robust policy solutions in coupled human-water systems. This goal was achieved by integrating a variety of models and approaches. The complete framework of the research consists of the following key components:

1. A localized SSP-RCP scenario framework by using stakeholders' storyline narratives in a participatory modeling approach along with global SSP scenarios
2. A quantitative integrated dynamic model, based on qualitative participatory models, using a system dynamic modeling approach along with an uncertainty quantification approach to incorporate a higher level of uncertainty (*i.e*., deep uncertainty) in the models.
3. A multi-scenario multi-objective robust optimization model for discovering optimal and robust solutions
4. A robust-resilient framework with a robust optimization model to consider resiliency of the system

Following this structure, the literature review is divided into four sections. The first section reviews the transdisciplinary approaches and scenario analysis in coupled human-water systems. Global SSP scenario frameworks are discussed as well. The second section focuses on participatory modeling approaches (*e.g*., storytelling) to quantify different types of uncertainty inherent in the system. In the subsections different concepts of deep uncertainty and their links to coupled human-water systems are discussed. The third section reviews system multi-objective robust optimization modeling in the context of simulating the dynamics of socio-economic processes. It includes subsections on robustness analysis and scenario discovery of the optimal solution in coupled human-water systems. The final section discusses resilience concepts related to the robustness of the systems and describes the developed integrated model in detail.

2.1 Transdisciplinary Approaches in the Study of Coupled Human-Water Systems

Natural and environmental resources are essential to human well-being and the economy of a society. Increasing pressure on environmental and water resource systems induced by human activities has resulted in socio-environmental issues in various regions of the world (Sterner et al., 2019). In the twenty-first century, significant environmental and socio-economic issues (*e.g*., population and global warming), are predicted to increase (Romps et al., 2014). Many environmental concerns, such as groundwater depletion, soil degradation, and soil salinity issues, have been exacerbated by the effects of global climate change, including climate extremes such as prolonged droughts, heatwaves, and floods (Alizadeh et al., 2017; Inam et al., 2017a,b). Beyond the hazards of ongoing degradation, the threat posed by these socio-environmental challenges to society is exacerbated by human dependence on environmental resources (*e.g*., coupled human-water systems), particularly in developing countries.

The increase in socio-environmental challenges requires an understanding of how global environmental change will impact society and how sustainable and integrated water resource management can mitigate the effects of multiple drivers (Sivapalan et al., 2012; Emmerik et al., 2014; Elshafei et al., 2015). Historically, water resource management has, rather than examining challenges from a holistic and systemic perspective, focused on specific domains (without addressing other potentially-affected components of the human-water system) (Blöschl et al., 2019). This management strategy may result in system failure and unsustainable outcomes (Halbe et al., 2013; Inam et al., 2017a,b; Malard et al., 2017; Halbe and Adamowski, 2019).

Coupled human-water systems are characterized by complex interactions between social and environmental components (Sivapalan et al., 2012; Baldassarre et al., 2013, 2015). Sustainability requires analyzing how society benefits from water systems and impacts them via dynamic feedbacks. To develop more sustainable policies for environmental and water management, frameworks that take into account the complex dynamics between society and the environment have become increasingly recognized (Elshafei et al., 2014). Interdisciplinary and transdisciplinary research in sustainability science is growing rapidly as a method for solving socio-environmental issues (McMillan et al., 2016). The integrated modeling of environmental and water resource systems attempts to examine complex socio-economic and environmental systems holistically (*e.g*., social, economic, hydrological, and ecological characteristics) (McMillan et al., 2016; Inam et al., 2017a,b).

2.1.1 Evaluating Socio-Environment Impacts Under the Projection of SSP-RCPs Ensemble

Climate change is a major source of uncertainty regarding the effects of environmental and socio-economic challenges on multiple domains, including water and food security, health, etc. Other sources of uncertainty, such as socio-economic development, political dependability, and the effects of substantial environmental degradation, amplify climate change and its accompanying implications especially in developing countries (IPCC, 2014). For instance, one of the most susceptible countries to climate change is Pakistan (the area of investigation for this research), where over 23.4% of the regional GDP is generated by agricultural production. Pakistan is home to 2.56% of the world's population, with 70% of its population residing in rural areas and nearly 45% of its labor force engaged in agriculture (State Bank of Pakistan, 2015, 2022). As a result of its reliance on agriculture and the scale of the predicted negative environmental implications of global warming in the region, Pakistan is extremely susceptible to climate change (SDPI, 2015).

Although climatic and socio-economic systems affect water resources simultaneously, the regional contributions of these systems and how they will evolve over time are mostly unclear. Most previous analyses have linked projected changes in water supplies to population growth, economic expansion, and accompanying demand increases, rather than compound climate system influences (Arnell, 2004; Alcamo et al., 2007; Hanasaki et al., 2012, 2013; Kiguchi et al., 2015). In addition, studies have quantified the proportional impacts of climate change and how they contribute to global and regional water resource issues (Haddeland et al., 2014; Veldkamp et al., 2016). Recent research on the interaction of socio-economic and climatic conditions has demonstrated the importance of addressing coupled human-water systems challenges at subregional scales in light of the impact of both human and climate systems (Veldkamp et al., 2016; Palazzo et al., 2017). Socio-economic impact assessments lack feedback and links between hydrological and socio-economic systems, despite recent advances (Veldkamp et al., 2016). Previous studies have not accounted for cross-sectoral feedback loops, dynamic interactions, stakeholder perspectives, and the combined future socio-economic and climate changes at local and regional scales. Recently, the international climate change community has developed a set of global scenarios, containing combinations of radiative forcing scenarios (Representative Concentration Pathways or RCPs) and socio-economic and policy scenarios [Shared Socio-economic Pathways (SSPs) and Shared Policy Assumptions (SPAs)], which can be used to investigate the effects of socio-economic and climate change. These scenarios can be applied in a global context or at smaller geographical scales to inform regional, national, and subnational planning (O'Neill et al., 2014). Regionally downscaled SSPs scenarios assist policymakers in developing robust water resources policies and agriculture and climate adaptation initiatives, while providing the scientific community with multiple improvement avenues that can be linked to adaptation assessments (Antle et al., 2015; Valdivia et al., 2015). However, the contributions of these scenarios on human-water systems and how they will change in the future are relatively unknown at regional scales. At finer scales, the identification and analysis of sub-global processes using bottom-up approaches through integrated regional modelling in the context of participatory modeling is needed to enhance the top-down approach such as shared socio-economic pathways (SSPs) with regionally contextualized assumptions and results.

2.1.2 Shared Socio-Economic Pathway (SSP) Scenarios

The SSPs are new socio-economic scenarios for use in global climate change studies. The SSPs represent five distinct worldwide scenarios (SSP 1–5) with fundamentally differing socio-economic circumstances. Each SSP has a quantitative and narrative (qualitative) scenario (O'Neill et al., 2014, 2017). The five SSPs can be put in a two-dimensional conceptual space where the horizontal axis indicates socio-economic adaptation challenges (Figure 2.1). Higher SSP values imply socio-economic situations that would make adaptation to climate change more challenging. The vertical axis represents socio-economic mitigation issues. Higher SSP values imply socio-economic factors that would make it harder to reduce greenhouse gas emissions.

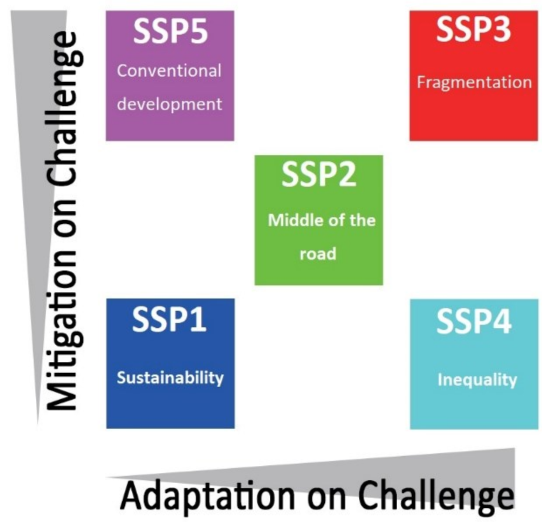

Figure 2.1 Adaptation and mitigation level of Shared Socio-economic Pathways (SSPs) (O'Neill et al., 2012).

SSP1 (Sustainability) represents a sustainable future in which it is simple to moderate and adapt to climate change due to the quick development of low-income countries, reduced inequality, rapid technological advancement, and a high degree of environmental degradation awareness. Additionally, agricultural land is equipped with yield-enhancing technologies.

SSP2 (Middle of the Road) describes conditions in which the socio-economic patterns of the last few decades persist. At historic rates, reductions in resource use and energy intensity are attained.

SSP3 (Fragmentation) indicates conditions in which it is challenging to reduce and adapt to climate change due to extreme poverty and a rapidly expanding population. In the energy sector, there is severe environmental degradation and slow technical change. Due to insufficient regional cooperation, the unsustainable use of local energy resources is exacerbated.

SSP4 (Inequality) depicts an extremely unequal world, both within and between nations. In industrial farming, crop yields would be high, but low in small-scale farming.

SSP5 (Conventional Development) offers a scenario in which adaptation is simple due to robust economic growth, but climate change mitigation is challenging because fossil fuels dominate the energy system. In this context, agroecosystems are highly maintained as a result of agricultural technology advancements. Land use management and water system management are typically quite resource intensive (Hanasaki et al., 2013; Riahi et al., 2017).

2.1.3 Participatory Narrative Storyline Development

Storytelling techniques are excellent methods for describing and expressing events through the medium of narrative storylines that convey information and better illustrate concepts (Hazeleger et al., 2015; Zscheischler et al., 2018). Storytelling enables individuals from a variety of disciplines, professions, and social backgrounds to better comprehend diverse ideas. Moreover, stories extracted from stakeholders and generated by local participants can provide researchers with a greater understanding of the system, while increasing model conceptualization, determining interactions and uncertainties, characterizing future scenarios, and evaluating model findings. Consequently, the concept of storytelling is highly effective for promoting meaningful stakeholder engagement (Alcamo, 2008; Trutnevyte et al., 2014). In addition, narrative approaches are appropriate for interactive modeling activities because they permit the examination of nonlinearities, multicausality, and complicated causal linkages. Thus, narratives are a valuable tool for informing and developing models of coupled human-water systems (Arico et al., 2001). In the present research, the storyline development approach was applied to the participatory modeling activities to gather narrative storylines and scenarios from stakeholders. In developing scenarios and corresponding simulations of vulnerability and adaptation options, we employed this powerful technique to extract the ideas and local expertise of stakeholders (Figure 2.2).

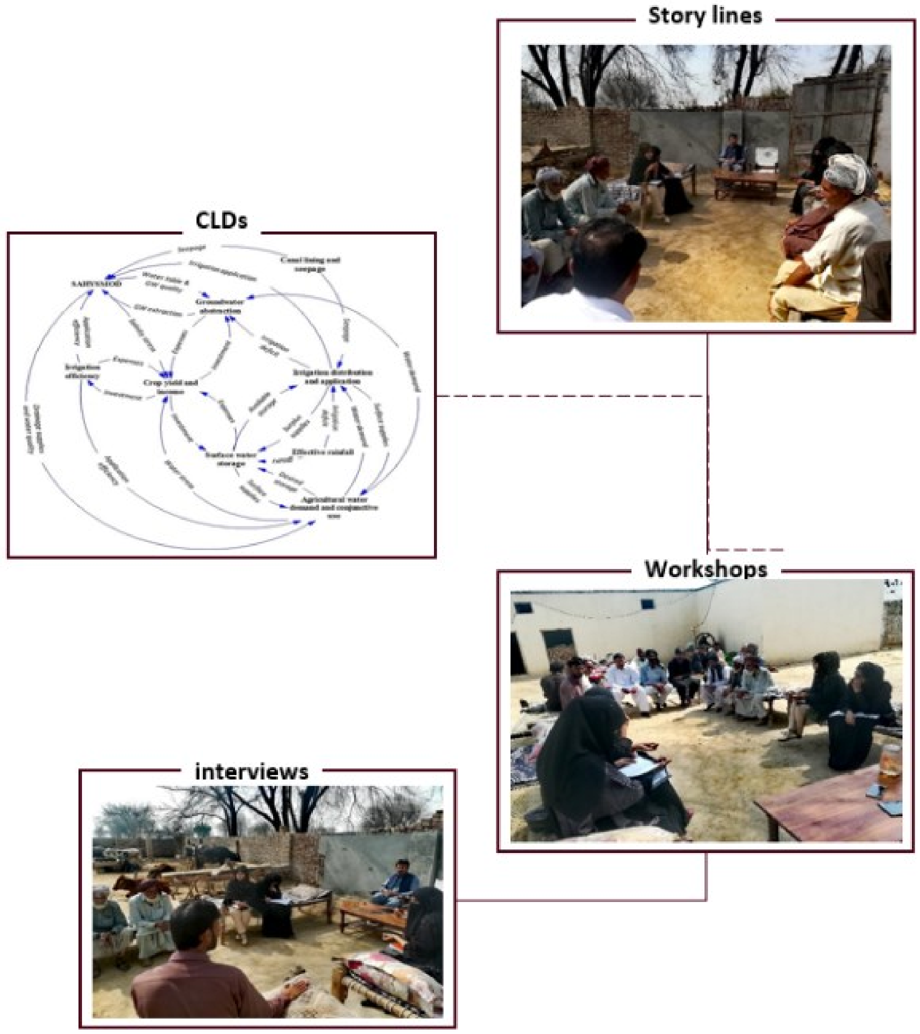

Figure 2.2 Development of narrative storylines in participatory activities with stakeholders in Pakistan's Rechna Doab watershed (the study area; picture credit: Azhar Inam)

Using a collection of SSPs-RCPs scenarios, this study attributes the simultaneous relative contributions of both human and climatic systems to water resource and environmental changes on a regional scale. By linking SSPs-RCPs and narrative storylines from stakeholders and simulating them using a coupled socio-economic and environmental system dynamics model, this analysis captures dynamic interactions between water and the human system that have previously been ignored in several human-water studies. This approach enables the use of a broad variety of socio-economic and climate futures that are very uncertain due to socio-economic and environmental consequences such as lack of fresh water, groundwater depletion, surface runoff, and soil salinity.

In this study, a set of stakeholder-generated regional narrative storylines and scenarios for the study area in Pakistan (from the first objective of this research) were quantitatively linked to the SSPs by employing regional stakeholder scenarios to critically examine and adapt SSP assumptions to the region. Through this procedure, a set of scenarios that focuses primarily on regional concerns and is also consistent with the SSPs is generated, allowing for an evaluation of the socio-economic impact of the scenarios.

2.2 Interactions, Uncertainties, and Vulnerabilities in Human-Water Systems

Understanding the dynamic interactions between natural systems and society, predicting future changes, and enhancing the sustainability and durability of human-water systems are currently among the most significant problems for water resources management. To address these issues, one must comprehend how decision-makers, science, and society view and characterize these issues (Sivapalan et al., 2018; Baldassarre et al., 2013). Enhanced participation of stakeholders, policymakers, and managers at all levels is essential for problem identification. In addition, stakeholder engagement is necessary to discover environmental and human behaviors in complex human-water systems that influence sustainable solutions and policy projections (Butler & Adamowski, 2015; Halbe et al., 2018).

Diverse system dynamics approaches have recently been created and applied to enhance our understanding of complex systems by capturing dynamic change and causal relationships across different dimensions and scales. Human-water systems, which include feedbacks between human and natural drivers, are typically regarded as coupled systems with complex dynamics and nonlinear interactions (Inam et al., 2017a,b; Malard et al., 2017, 2018). Such coupled approaches have been used in supporting decision-making in agricultural water resource management (Inam et al., 2015; Kraucunas et al., 2015; Hassan et al., 2014; Liu et al., 2008). Despite significant benefits from recent studies, a profound understanding of these systems' coupled and mutual drivers and their performance in human-water interactions is still in its infancy.

2.2.1 Uncertainty Quantification in Socio-Economic and Environmental Systems Through Exploratory Analysis

Coupled human-water models offer opportunities to enhance knowledge of future socio-economic changes and climatic concerns in complex, dynamic socio-environmental systems (Girard et al., 2015; Reed and Kollat, 2012). These types of models can better assess the effects of future climate and socio-economic changes on environmental systems because they can account for the interactions between subsystems such as agriculture and the economy, as well as the political, environmental, and hydrological interactions corresponding to these subsystems (Harou et al., 2009; Kasprzyk et al., 2013). Although integrated simulation models are useful tools for modelling non-linear variable changes in socio-economic and environmental systems and their associated spatiotemporal dependencies, the potential vulnerabilities of such coupled human-water systems to deep uncertainties are not investigated thoroughly in the literature. Deep uncertainty defines situations where decision-makers cannot agree on (*i*) appropriate conceptual models representing the interrelationships of the major drivers that shape unknown future conditions, (*ii*) probability distributions of variables in conceptual models that characterize their uncertainty, and (*iii*) comparative assessment of potential outcomes (Lempert et al., 2003; Kasprzyk et al., 2013; Herman et al., 2014). In complex coupled human-water systems, where a mix of socio-economic and environmental changes affect the system and produce unanticipated outcomes, deep uncertainty is extensive.

2.2.2 Deep Uncertainty

Prediction of change is crucial to policymaking in complex systems, especially for long-term planning in unusual circumstances. For instance, decisions involving climate change, future demand forecasts, the design of infrastructure, technology advancement in societal and environmental sectors, and financial crises are characterized by high levels of uncertainty. Ignoring such uncertainties might result in policies with negative results; hence, policymakers must examine frameworks to avoid unexpected effects (Walker et al., 2018).

Overall, uncertainty can be defined as a lack of awareness due to a deficiency of information. Uncertainty in decision-making refers to the gap between known information and the knowledge decision-makers require to design or implement a policy that meets the desired objectives over a spectrum of conceivable futures. Various elements of a system may be accompanied by uncertainty (*e.g.*, the decision-making domain, exogenous factors, system outcomes, and the importance of outcomes as defined by stakeholders) (Pruyt and Coumou, 2012; Tegeltija et al., 2018; Eker and Kwakkel, 2018).

Recent policymaking research has focused more on decision-making in contexts characterized by high degrees of uncertainty. Numerous ways have been developed to help decision-making under uncertainty, taking into account multiple dimensions of uncertainty. The three identified dimensions of uncertainty are defined as the (*i*) location of uncertainty in the policy analysis framework (*i.e.*, external context, the system model, outcomes, or weights of the outcomes), (*ii*) level of uncertainty (the degree or severity of the uncertainty), and (*iii*) the nature of uncertainty (Walker et al., 2003; Kwakkel et al., 2010). Uncertainty in a situation might result from a lack of knowledge about the system, the system's inherent variability, or discrepancies in how decision-makers and stakeholders perceive the system's status (*i.e.*, ambiguous conditions) (Brugnach et al., 2008). Table 2.1 summarizes the main types of uncertainty in complex systems.

Table 2. 1 Different Types of Uncertainty (Adapted from Walker et al., 2013)

Level of uncertainty	Description of situation	Analysis methods
Little uncertainty	Is knowable	Predictions and actions
Statistical uncertainty	Will behave in much the same way as in the past	Trend-based analysis
Scenario uncertainty	Is well described by a few overarching scenarios	Static robust (Optimization)
Deep uncertainty	Is unknown or disagreed upon by experts and/or stakeholders, with no consensus on which adaptive policies and/or actions the future might bring	Adaptive policy actions

The exchange of point forecasts for best-estimated joint probability distributions over future states of a system is insufficient to adequately account for uncertainty. A diversity of perspectives and ideals, as well as underlying uncertainty regarding the outcomes of our actions, are fundamental features of our world (Sen, 2009). Consideration of these two fundamental variables during decision-making can enable prominent, dependable, and accurate conclusions regarding complicated issues such as human-water systems and climate change.

The objective of the literature on scenario development, iterative risk management, and risk governance is to develop frameworks for engaging stakeholders in settings where uncertainty occurs owing to diverse/inconsistent problem perceptions (IPCC, 2012). Neglecting the primary role of uncertainty can impede any effort to enhance policymaking about new, complicated challenges, particularly if they must be managed for the long-term and larger-scale benefit of a larger community (Glynn et al., 2017).

2.2.3 Deep Uncertainty in Coupled Human-Water Systems

The management of water resources has the problem of establishing policies and adaptation measures to reduce vulnerability in the face of socio-economic and climate change (Füssel, 2007; Hallegatte, 2009). In decision-making procedures for long-term hydroclimatic forecasts, simulation and optimization techniques have been widely implemented. Nonetheless, these projections are unclear duee to a wide variety of uncertainties, including climate model variability, socio-economic changes, and human-water system concerns (Herman et al., 2019; Wilby & Dessai, 2010). Top-down (scenario-based) techniques aim to accurately predict the future climate of a region using probabilistic forecasts of climatic variables to enable climate change adaptation planning and strategies (*e.g.*, water resources management). Following these forecasts, policymakers develop plans based on the forecasts and then make a final decision. The general concept is to first comprehend how the future is likely to develop, and then formulate policy alternatives and actions based on this comprehension.

Top-down techniques in decision-making domains rely on scientific understanding and general-purpose modeling of regional climate change (*e.g.*, by defining a probability distribution) without considering the particulars of the decision context.

Although the deployment of ensemble projections such as SSP-RCPs can considerably aid policymaking under uncertain future conditions of human-water systems, top-down ensemble projections can only capture a portion of severe (deep) uncertainty (Helgeson, 2018; Stainforth et al., 2007). A concern with such approaches is that particular variables or processes are routinely prioritized in methodological decisions to generate more accurate estimates for some variables than others (Parker and Winsberg, 2018; Parker, 2014). The complexity of measuring uncertainty associated with regional climate change estimates is an additional issue. For instance, suppose that the planning of policies is based on their success in the most probable future. In such a scenario, the set of optimal policies may be inaccurate or insufficient if uncertainty about potential futures is not adequately defined (*i.e.*, the projections are revealed to be presumptive). Under such circumstances, conventional decision-making techniques that require probability and corresponding values, such as cost-benefit analyses and anticipated value theory, may not be applicable (Lempert, 2015; Borgomeo et al., 2018; Herman et al., 2019).

In the climate change adaptation literature, there has been a recent shift towards bottom-up approaches to complement the conventional top-down approach (Lempert et al., 2003, 2006; Dessai et al., 2009; Brown and Wilby, 2012; Helgeson, 2018). A bottom-up approach (also known as vulnerability-first, policy-first, or assess-risk-of-policy) formulates the problem by understanding the unique choice context as opposed to the broader climatic conditions. These bottom-up approaches have rapidly improved through frameworks such as Info-Gap (Hipel & Ben-Haim, 1999; Korteling et al., 2013), Decision Scaling (Brown et al., 2012; Poff et al., 2016), and Robust Decision Making (Lempert, 2003; Bryant & Lempert, 2010). However, uncertainty analysis in coupled integrated human-water water resource models has been essentially nonexistent, with the exception of Monte Carlo simulations, which are not suitable for dealing with deep uncertainty. In this study, we address these challenges by employing a machine learning technique known as scenario discovery (Bryant & Lempert, 2010) to assess the magnitude of uncertainty in complex human-water systems. When constructing adaptable, flexible, and robust strategies, it is crucial to account for the impact of deep uncertainty on complex human-water systems. By merging top-down and bottom-up methodologies with a non-deterministic, possibility-based approach, this research seeks to explain the deep uncertainty in coupled socio-economic-environmental system dynamics models. Systematic scenario discovery is done in an exploratory approach to identify vulnerabilities across a spectrum of potential futures in the context of the uncertainties associated with the ensemble RCP-SSPs.

2.2.4 Scenario Discovery: A Model-Based Approach to Scenario Development

Scenario discovery is a method for overcoming the issues of describing and expressing simulation models' deep uncertainty (Dalal et al., 2013). In this strategy, the effects of a simulation model's numerous deep uncertainties are carefully investigated through a series of computational experiments (Kwakkel and Jaxa-Rozen, 2016). The generated data set is then evaluated to find locations of interest in the space of uncertainty (Bryant & Lempert, 2010; Kwakkel and Jaxa-Rozen, 2016). These chosen regions can subsequently be communicated to stakeholders and decision-makers through narratives. "Open exploration" and "directed search" are the two fundamental search methodologies utilized in scenario discovery.

Scenario discovery is utilized because scenario building can be challenging when multiple parties with divergent interests and perspectives are involved (Bryant and Lempert, 2010). Additionally, scenario development tends to overlook unexpected developments and discontinuities (Derbyshire and Wright, 2014; Van Notten et al., 2005; Kwakkel and Jaxa-Rozen, 2016). This may be partially attributable to the fact that many scenario models reduce a large number of significant uncertain aspects to a smaller number of drivers or megatrends. With this dimension reduction, realistic and intriguing combinations of uncertain developments are eliminated. In contrast, scenario discovery first thoroughly investigates the effects of all relevant elements and then performs dimensionality reduction in light of the resulting outcomes, thus potentially uncovering unanticipated results that would have been overlooked by standard scenario techniques (Kwakkel and Jaxa-Rozen, 2016).

2.3 Multi-Objective Robust Optimization for Managing Deeply Uncertain Human-Water Systems Using Directed Search

Complex human-water systems cannot be planned and managed based on the limited definition of optimality of a single most probable future scenario. In such cases, there is a critical need to find robust management plans that perform effectively over multiple possible system conditions (Herman et al., 2014; Kwakkel et al., 2016). Optimality criteria refer to the conditions that must be met by a function in order for it to be considered optimal. Optimality is always required in the execution of any decision-making process. When planning in high-dimensional environments, maintaining optimality as a criteria can be an extremely challenging undertaking (Null et al.,2021). Using some realistic assumptions about the surroundings, we can come up with a solution that best meets the criteria of optimality and completeness without requiring excessive calculation effort. Optimality criteria methods are generally referred to as optimization models using numerical methods. Iterative strategies that rely on optimality criteria or other heuristic principles to find an optimal solution in a system are called optimality criteria methods (Arora, 2004; Herman et al., 2014).

There are various definitions of robustness. The capacity of a system to withstand disturbances and changes without adjusting its initial stable structure (Hampel, 1971; Giuliani and Castelletti, 2016) is referred to as stability in general systems analysis; in computer science, it refers to the degree to which a system or element is able to operate adequately despite incorrect inputs or hectic environments (Geraci, 1991); in biological science, it refers to the persistence of a characteristic or feature in a system despite disturbances (Félix and Wagner, 2008).

Typically, robustness in water supply systems is defined as the ability to function satisfactorily in the face of a broad range of realistic future scenarios or events (Hashimoto et al., 1982; Groves et al., 2008). As part of water resource management research, alternative definitions of system robustness have been examined, including exploratory modelling and analysis (Kwakkel and Pruyt, 2013), regret-based measures and sensitivity controls (Herman et al., 2015), applications of Maximin or Minimax theory (Giuliani and Castelletti, 2016), as well as alternative satisficing practices that integrate Monte Carlo analysis and decision scaling (Steinschneider et al., 2015). In Chapters 6 and 7, we describe a quantitative analysis that defines robustness as the proportion of future scenarios that result in acceptable outcomes. System performance is an excellent tool for analyzing a wide range of highly variable, discrete future situations, as it elicits a visible, quantified estimate of robustness, and has been used in a number of recent water resources management research projects (Beh et al., 2015; Herman et al., 2014). The robustness metric has been the focus of numerous research studies related to water resources management adaptive planning (Lempert and Groves, 2010; Moody and Brown, 2013; Haasnoot et al., 2013; Jeuland and Whittington, 2014; Kwakkel et al., 2015).

Dealing with deep uncertainties necessitates a shift in the policymaking goal from optimality to robustness in order to produce the intended outcomes with less sensitivity to uncertainty (Chandrasekaran, 2005). Through the interactive exploration of futures with a wide range of plausible scenarios, robust adaptations can be identified that perform well in contrast to other strategies (Lempert, 2003). Portraying many likely future scenarios inside a system can allow stakeholders to explore and assess the system risks, even under deep uncertainty (Groves and Lempert, 2007; Groves et al., 2015; Forni et al., 2016).

Moreover, decision-making under a high level of uncertainty is difficult due to several political, social, and technical reasons (Pfaff et al., 2013). Policymakers consistently face new challenges within complex dynamic human-water systems due to continuously changing socio-environmental conditions related to climatic (*e.g.*, drought, flooding, heatwaves) and socio-economic (*e.g.*, population growth, increasing water demands, land-use change, intensification of irrigated agriculture and groundwater depletion) drivers (Joyce et al., 2011; Vogel et al., 2015). Addressing these challenges necessitates a new robust policymaking framework that can represent the complexity of socio-environmental systems. Robust policymaking that incorporates diverse stakeholder objectives within computer modelling and considers associated deep uncertainties as part of a participatory process can facilitate tackling complex systems problems under uncertainty.

Earlier studies on human-water systems (Wu et al., 2013; Beh et al., 2017; Ren at al., 2019; Yuan et al., 2022) have focused mainly on optimizing management policies to maximize or minimize some utility functions representing economic or environmental objectives (*e.g.*, groundwater drawdown, soil salinity). Merging these objectives into a single expected utility function raises several problems. First, it makes assumptions about stakeholders' values and the homogeneity of these values under changing conditions. Restricting socio-environmental objectives to find a single optimal solution fails to capture the full range of feasible objective values, which may better represent the range of preferences between different stakeholders. Second, optimizing the expected value of an objective function needs unanimity on the probability distribution of stochastic inputs, which could be problematic for socio-environmental systems with deeply uncertain features (Quinn et al., 2017).

Robust policymaking addresses the problem of deep uncertainty by changing the emphasis of policy design from finding optimal solutions to investigating robust solutions that provide acceptable performance over many plausible future scenarios (Bankes, 2002). In the robust policymaking procedure, instead of assigning probabilities to the future states and determining the most likely one, the ensemble of future conditions is considered as a set of computational experiments and used to recognize ranges of deeply uncertain drivers for which a specific policy option performs unsatisfactorily (Groves and Lempert, 2007; Lempert and Groves, 2010). In this method, threshold values for the deeply uncertain factors that will affect the performance of policy options the most are defined, which allows decision-makers to examine the consequences of likelihoods of future scenarios which affect the system remarkably (Bryant and Lempert, 2010). Then a robust strategy that performs satisfactorily across a range of plausible states can be selected by decision-makers.

2.3.1 Multi-objective Robust Decision-Making Framework

Appropriate prediction approaches, such as optimization techniques, can be used to supplement exploratory data and produce more robust policies. In this regard, multi-objective optimization strategies and meta-heuristic algorithms can be efficiently applied for objective optimization in robust decision-making under severe uncertainty (Roach et al., 2018; Beh et al., 2015). Recently, the framework for multi-objective robust decision-making (MORDM) has sought to explicitly incorporate the trade-offs between environmental objectives and the uncertainty surrounding model parameters (Hadka et al., 2015; Ward et al., 2015). MORDM employs global optimization with multi-objective evolutionary algorithms (MOEAs) to identify trade-offs across a broad spectrum of planning choices. When a randomly selected solution is unfeasible or unsatisfactory due to the complexity of the water resources system, MOEAs attempt to compensate for this deficiency in alternatives by seeking for premium solutions prior to evaluating their robustness (Kasprzyk et al., 2013; Reed et al., 2013). Multi-objective robust decision-making uses a statistical rule induction approach to identify the threshold values of deeply unknown variables over which system performance falls below user-defined restrictions. These significant improvements help decision-makers comprehend the critical trade-offs, dependencies, and vulnerabilities in their management policies. MORDM searches for trade-off solutions with: (*i*) optimal performance for the best available projection of the future, and (*ii*) negligible performance reductions under deeply uncertain factors (*i.e.*, robust satisfying behaviour). For integrated water resources planning and management, representing socio-economic and climate change scenarios with probabilistic likelihoods is a severely challenging issue that has not been resolved. MORDM distinguishes itself from other techniques such as Decision Scaling (Moody and Brown, 2012) and the Info-Gap theory (Ben-Haim, 2010; Hall et al., 2012) by enhancing the ability of decision-makers to discover potential policy options, recognize their trade-offs, and take robustness constraints into account. This research advances the MORDM framework by demonstrating the benefits of using the multi-scenario version (Stewart et al., 2013) to identify adaptive, robust policy options for coupled human-water systems and to analyze the robustness of management strategies for sustainable water resource management under all defined scenarios (*e.g.*, in out cases, localized SSP scenarios).

2.4 Resiliency in Coupled Human-Water Systems

Unlike robustness, which describes a water system's ability to perform under diverse future conditions, some specific performance metrics such as reliability, vulnerability and resilience describe how the system will perform under a particular scenario. For assessing the effectiveness of water resource systems, reliability, vulnerability, and resilience are the most commonly used performance metrics in the water resources management literature. In general, reliability performance requirements are concerned with the frequency at which a system fails. Vulnerability is defined by how severe the consequences of failure may be in the system whereas resiliency describes how quickly a system can recover from a failure after experiencing a perturbation (Hashimoto et al., 1982).

The integration of resilience into the coupled human–water system modeling is crucial in the Anthropocene, when human and water systems must deal with perturbations from each other (Mao et al., 217; Falkenmark et al., 2019). Coupled human-water systems are experiencing interconnected paradigm shifts because of the complex links between human and water systems (Rocha et al., 2018). Humans and water systems are likely to be affected in different ways when their resilience changes. A conceptual framework proposed by Mao et al. (2017) to describe socio-hydrological resilience suggests that human-water interactions contribute to this resilience. Studies spanning sustainable water use and development (Pahl-Wostl et al., 2013), hydrological risk management (Paul et al., 2018;), and freshwater ecosystem protection (Bisson et al., 2009) have highlighted the importance of resilience in a coupled human-water context.

There are numerous definitions of resilience. It is commonly used in a wide range of fields and circumstances (Fletcher and Sarkar, 2013; Southwick et al., 2014). A system's resilience describes its ability to absorb disturbances without significantly degrading its performance or form (Walker et al., 2004). A broader definition of resilience is the ability to perform despite constant change and persist in the face of perturbations (Scheffer et al., 2001; Folke et al., 2016). Accordingly, this term refers to a system conceptualized in three dimensions of absorbent, adaptive, and transforming capabilities and permanence for the present, and a reaction to future changes (Xu et al., 2022).

In coupled human-water systems, resilience is the ability of the system to maintain the desired conditions for both humans and the water components during interactions between the two. It refers to the system's ability to resist not only socio-environmental threats and climate change, but also internal disturbances arising from human-water interactions (Mao et al., 2017; Xu et al., 2022). To maintain the full function of the human water system, for example, groundwater extraction for agricultural purposes may need to be drastically reduced throughout the entire watershed, which would result in a big adjustment to many water sectors. Accordingly, to develop a resilient coupled-human system, it is essential to manage conflicts and trade-offs between stakeholders with conflicting preferences and objectives. These issues could be addressed by resilient robust policy design, since they link the water resources management and the preservation of the water supply across multiple societal levels, guiding the resource towards a desirable state (Pahl-Wostl, 2015). However, defining what conditions are acceptable across diverse societal stakeholder groups requires interdisciplinary and transdisciplinary approaches involving multiple stakeholders at multiple levels.

As an example of resilience in human-water systems, the "levee effect" scenario is ideal (Di

Baldassarre et al., 2013). Humans benefit from floodplains for numerous reasons, including fertile soil. However, population growth and development strategies for these regions must maintain a safe distance from rivers with considerable flooding danger. With the installation of levees, the distance considered "safe" has decreased. Technology has continued to enhance the resilience of water systems to flood disasters, but there is a risk that, over the long term, social resilience to catastrophic events such as extreme flooding and bank breaches will be reduced due to the increasing disturbances of slow variables, including human-induced water system interventions and climate-related hydrological change (Xu et al., 2022). This implies examining resilience dynamics across different scales in the study of coupled human-water systems properties (Konar et al., 2019; Dewulf et al., 2019).

The purpose of this study is to define how resilience is understood in order to clarify its relationship to other concepts such as robustness, particularly in regard to coupled human-water systems' characteristics and capabilities.

2.5 Summary

This chapter focussed on a literature review that introduced and discussed several key facets of this research and compared their novelty to approaches existing in the literature. The new methods discussed in this chapter include the following aspects.

This study represents the first extension of the multi-scenario multi-objective robust optimization framework to a regional complex human-water system with multiple interacting stakeholders using an integrated system dynamics model under deep uncertainty and SSP scenarios. The approach is used to explore robustness by managing key uncertainties in the system. The method is helpful in a regional multi-stakeholder human-water system, where the interactions of each submodule can impact the future robustness of the system under different conditions of SSP scenarios. Robust policymaking in human-water systems is a promising pathway for managing water resources more efficiently under changing socio-economic and climate conditions in developing societies.

Therefore, this research describes a policymaking support framework that combines a scenario elicitation framework, coupled socio-environmental system modelling, and multi-scenario multi-objective robust policymaking within a participatory and interactive process for sustainable policy planning. Such optimal robust planning must account for uncertainties and imperfect knowledge about the future. The proposed framework contributes to the literature by developing a robust policymaking framework for adaptive decision support in socio-environmental systems that aids knowledge exchange and participation within complex dynamic human-water systems decision spaces in areas facing different adaptation challenges.

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CONNECTING TEXT TO CHAPTER 3

This chapter describes the development of a unique and effective stepwise approach to identifying and engaging stakeholders' storyline narratives in developing a set of localized SSR-RCP scenario frameworks. The approach developed aids in mapping key drivers of socio-environmental and climate changes from global SSPs and explicitly incorporates stakeholders' views in localizing /downscaling those scenarios. The integrated dynamic model then was used to simulate the vulnerability of the considered coupled human-water system in Pakistan by using the developed localized SSP-RCP scenarios. Therefore, the developed framework provided a holistic view of the whole coupled system with socio- economic and physical process interactions.

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The author of the thesis was responsible for the development, testing, and application of the different methods and wrote the manuscript presented here. Prof. Adamowski, the supervisor of this thesis, provided valuable advice on all aspects of the research and contributed to the review and editing of the manuscript. Dr. Azhar Inam, Assistant Professor in the Department of Agricultural Engineering at Bahauddin Zakariya University in Pakistan, conducted data collection and storyline narratives.

CHAPTER 3: **Integrated Assessment of Localized SSP–RCP Narratives for Climate Change Adaptation in Coupled Human-Water Systems**

Mohammad Reza Alizadeh, Jan Adamowski, Azhar Inam

Abstract

The assessment of climate change impacts requires downscaled climate projections and context-specific socio-economic scenarios. The development of practical climate change adaptation for environmental sustainability at regional and local scales, is predicated on a strong understanding of future socio-economic dynamics under a range of potential climate projections. We have addressed this need using integrated assessment modeling of a localized hybrid Shared Socio-economic Pathway - Representative Concentration Pathway (SSP-RCP) framework, through an interdisciplinary and participatory storyline development process that integrates bottom-up local expert-stakeholder knowledge with top-down insights from global SSPs. We expend the global SSPs (SSP1 to SSP5) as boundary conditions in conjunction with climate change pathways (RCP4.5, RCP8.5) to create localized SSP narratives in an iterative participatory process, using a storytelling method. By using an integrated socio-economic and environmental system dynamic model developed in collaboration with local stakeholders, we explore the potential impacts of plausible local SSP-RCP narratives and quantify important socio-environmental vulnerabilities of a human-water system (e.g., crop yields, farm income, water security and groundwater depletion) by the mid-century period (i.e., by 2050). The framework is developed to inform climate adaptation for Pakistan's Rechna Doab region, which serves as a representative case of a multi-stakeholder coupled human-water system operating in a developing country. Our results suggest that even under limited socio-economic improvements (e.g., technology, policies, institutions, environmental awareness) water security would be expected to decline and environmental degradation (e.g., groundwater depletion) to worsen. Under RCP 4.5, the average projected increase in water demand in 2030 will be about 7.32% for all SSP scenarios narratives, and 10.82% by mid-century. Groundwater use varies significantly across SSPs which results in an average increase of about 29.06% for all SSPs. The proposed framework facilitates the development of future adaptation policies that should consider regional and local planning as well as socio-economic conditions.

Key Words: SSP–RCP scenario framework, Local socio-economic scenarios, Integrated system dynamic modeling, Participatory approach, Storytelling, Climate adaptation

3.1 Introduction

Given the uncertainty regarding the complex interactions between humans and environmental systems, plausible future change scenarios can serve as strategic management tools to explore the potential impacts of these changes, and inform adaptation decision-making (O'Neill et al., 2020). In the past decade, several communities have worked in concert to develop the Shared Socio-economic Pathway–Representative Concentration Pathway (SSP-RCP) scenario framework, an umbrella-term that encompasses various socio-economic development pathways (SSPs) and greenhouse gas concentration trajectories (RCPs), along with their corresponding climate change effects (Ebi et al., 2014; Van Vuuren et al., 2014; Kriegler et al., 2014; Kebede et al., 2018; Graham et al., 2020). Through the parallel approach of a SSP-RCP framework, climate and societal futures can be developed simultaneously, providing integrated climate change scenarios. One of the main problems with broad, general SSP-RCP scenario frameworks is their coarse resolution, typically national or global. Sustainable policy decisions require a site-specific approach and detailed information adapted to finer scales (i.e., local or regional). Providing a multi-scale approach that incorporates both site-specific knowledge and stakeholder perspectives, is essential to the successful regional or local scale application of a global SSP-RCP scenario framework. In recent years, an increasingly diverse range of perspectives and users have emerged around localized SSP-RCPs, allowing them to be applied at different time and spatial scales (Absar and Preston, 2015; Nilsson et al, 2017; Rohat et al., 2018; Chen et al., 2019; Iqbal et al., 2019; Reimann et al., 2021). For example, using a set of SSP and RCP scenarios without the participation of local stakeholders, Mehboob et al. (2021) evaluated the influence of climatic and socio-economic changes on future surface water supply in Pakistan's Upper Indus Basin. Further, with the participation of local stakeholders, European extensions of SSPs have been developed (Kok et al., 2019) and applied as a framework for regional SSPs. To enrich decision-makers' understanding of adaptation and mitigation options, downscaled climate scenarios based on such regional SSPs have been used in conjunction with two climate change impact models (Harrison et al., 2019; Frantzeskaki et al., 2019). However, in terms of regional/local scales and quantification of plausible futures, SSP-RCP scenarios are poorly understood and their contribution to developing sustainable policy decisions for coupled human-water systems remains unknown.

Human-water systems at local and sub-regional levels are constrained by conditions arising from the regional context that are, in turn, affected by related internal politics associated with specific socio-economic circumstances. This means that any multi-scale scenario framework must consider the different scales at which the diversity of socio-economic change will occur (e.g., Biggs et al., 2007; Zurek and Henrichs, 2007; Schweizer and Kurniawan, 2016). However, stakeholders' knowledge and concerns must be included in order to develop scenarios that are relevant to local socio-economic conditions. This requires substantive stakeholder engagement in a supportive participatory process (Alcamo, 2008; Zscheischler et al., 2018; Allan et al., 2021). When scaled up, regional integrated modelling in the context of participatory modeling must be used to incorporate bottom-up analyses of local processes into top-down approaches, e.g., like SSP-RCP frameworks. Using a combination of expert-based and participatory methods allows for the development of well-balanced scenarios through hybrid top-down and bottom-up approaches across multiple scales, ranging from global to regional and short-term to long-term (van Ruijven et al., 2014). Moreover, climate projections at regional and local scales need to be downscaled to be compatible with projected societal trends. When it comes to local impacts that disseminate beyond borders into other socio-economic realms, it is equally challenging to specify consistent future conditions (Challinor et al., 2017). Therefore, careful evaluation and quantification of the plausible combinations of climate and socio-economic futures at regional/local scales are required.

Previous studies have sought to extend the SSPs' relevance for decision-making; however, none of these studies focused on regional integrated modeling of localized SSP-RCPs as a tool that can provide local stakeholders with data and information to inform local adaptation decisions. In this study, we developed a local scale hybrid SSP-RCP scenario framework to address these needs and challenges. This study builds upon previous studies by simulating the local SSP-RCP narratives to produce spatial and temporal projections of variables of interest for quantifying potential water resources hazards and vulnerabilities in a human-water system at the local level. Local narratives along with the projections are used to assess the impacts of important socio-economic and climate change-related risks. The proposed framework is notable for: (i) a storytelling approach to gather narratives for downscaling global SSPs to frame the hybrid local SSP-RCP narratives; (ii) a regional integrated system dynamic model developed with local stakeholders; and (iii) assessing the impacts of a variety of profoundly uncertain socio-economic and climate scenarios on a multi-stakeholder human-water system in a developing country.

We extend the global SSPs (SSP1 to SSP5) combined with climate change pathways (RCP4.5, RCP8.5) within Phase 5 of the Coupled Model Intercomparison Project (CMIP5), as boundary conditions to create localized SSP narratives in an iterative participatory practice using a storytelling method. We then employ a regional integrated socio-economic and environmental system dynamic model, developed with stakeholders, to explore the potential impacts of plausible SSP-RCP narratives and quantify important mid-century (up to 2050) socio-environmental-related vulnerabilities of Pakistan's Rechna Doab region, which serves as a representative case of a multi-stakeholder coupled human-water system. The proposed framework provides an analytical representation for the impact assessment of climate and socio-economic change across local scales. The present study's proposed framework will serve to increase our understanding of how: (i) calibrating global models with regional scenarios can help balance local narratives with global perspectives, (ii) regional integrated models can provide for a rigorous evaluation and quantification of SSP-RCP narratives and, (iii) in the context of developing countries, the implications of future climate change and socio-economic uncertainty regarding water resources and the environment of human-water systems can be identified.

3.2 Study Area

To gain insight into human-water systems in a developing country, the study focused on the extensive irrigated regions of central-northeastern Pakistan's Rechna Doab watershed (Figure 3.1). Located in Pakistan's portion of the Indus Plain, the watershed covers roughly 732.5 km2 in the Ravi and Chenab Rivers' inter-fluvial basin (lat. 30°32'–31°08'N, long. 72°14'—71°49' E). The Indus Plain harbours one of the largest contiguous irrigation systems in the world, extending over 160 × 103 km2 and drawing upon 128 km3 yr-1 in water diversion (Ahmad, 2002; Inam et al., 2017a, b). Pakistan's Punjab region is one of the oldest and most highly developed irrigated regions in the world. The major summer (kharif) crops are rice (Oryza sativa L.), cotton (Gossypium hirsutum L.), and forage, whereas wheat (Triticum æstivum L.) and forage are the winter (rabi) crops. Summer temperatures range from 21°C to 49°C, with a long, hot season lasting from April through September. The winter season runs from December through February, with maximum daytime temperatures ranging from 25°C to 27°C and a few nights below 0°C. Climatically, spring and fall are short. Of the roughly 400 mm yr-1 in precipitation, 75% occurs during the June to September monsoon season (Ahmad, 2002; Inam et al., 2017a, b). Due to the scarcity of surface water, farmers irrigate their crops with groundwater that is of marginal quality due to salinity (Rehman et al.,1997; Arshad et al., 2019). Rechna Doab has wide-ranging socio-economic and environmental conditions with regard to the various stakeholders involved in water resource management (Table 3.A.3 in the supplementary material). This provided an excellent opportunity to compare, test and evaluate the effectiveness of the proposed participatory localized SSP–RCP scenarios framework.

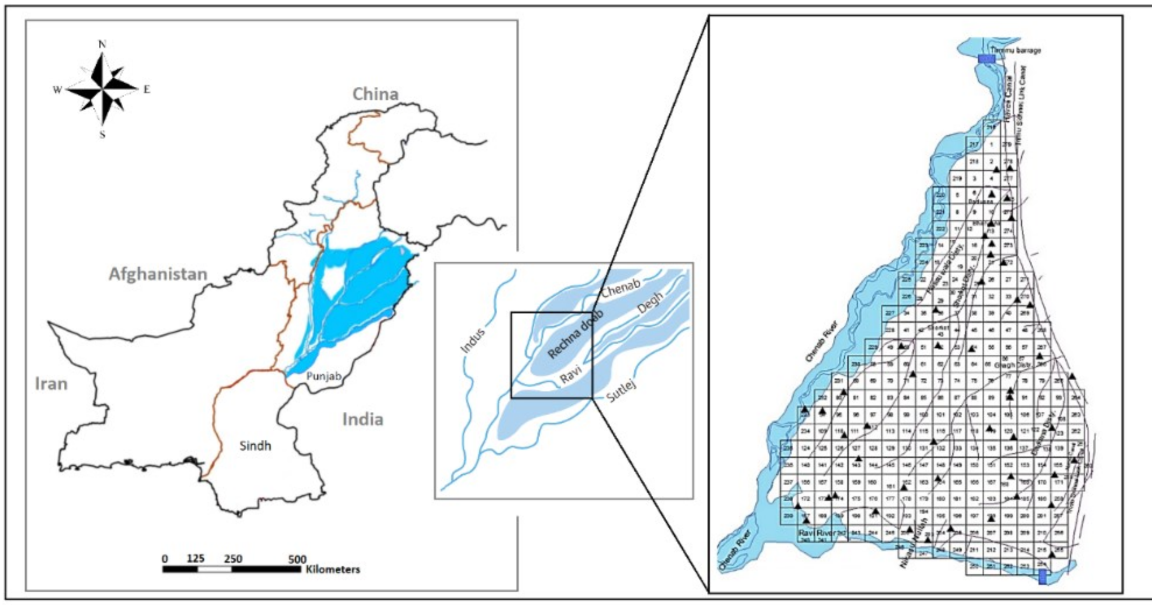

Figure 3.1 Study area in Pakistan's Rechna Doab basin.

3.3 Methods

A comprehensive impact analysis of different socio-economic and climate change scenarios was undertaken to assess the vulnerability of the human-water system under consideration. The relative effects of socio-economic and environmental drivers were quantified at regional/local scales across global futures that included five different socio-economic conditions (the Shared Socio-economic Pathways, SSPs) and two climatic conditions (the Representative Concentration Pathways, RCPs). The five SSPs and two climate change scenarios RCPs (climate forcing scenarios 4.5 and 8.5) were combined to develop ensemble SSP-RCP scenarios. We selected a moderate scenario of RCP 4.5, which we deemed likely given the current trends and also a "worst-case" scenario under the extreme conditions represented in RCP 8.5 (Tebaldi et al., 2021). These scenarios were in line with the assumptions of our study in terms of relative future socio-economic and climate changes.

These various combinations of socio-economic and climate change scenarios were downscaled, adjusted, and localized based on stakeholder-led narrative scenarios. A regional integrated socio-economic and environmental system dynamics model developed with stakeholders during participatory activities was then run under an ensemble of downscaled SSP-RCP scenarios to determine vulnerabilities of the human-water system for the overall region. An analysis of the short-term (up to 2030) and medium-term (up to 2050) impacts of different socio-economic drivers (e.g., GDP, population, technology development, environmental awareness), and climate change factors (e.g., precipitation, temperature) was then undertaken. By applying an ensemble of SSP-RCP scenarios, both climate and socio-economic change could be simultaneously affected at the regional/local level. Using scenarios derived from SSP-RCP and narratives from stakeholders and the regional integrated socio-economic and environmental system dynamics model, this study sought to capture dynamics interactions overlooked in prior research on human-water systems. Figure 3.2 illustrates the integrated scenario framework application in more detail, highlighting how it can effectively be applied across regional and local scales of interest. In the following sections, we present the key assumptions and procedures used in the development of the different scenario components at the regional and local scales.

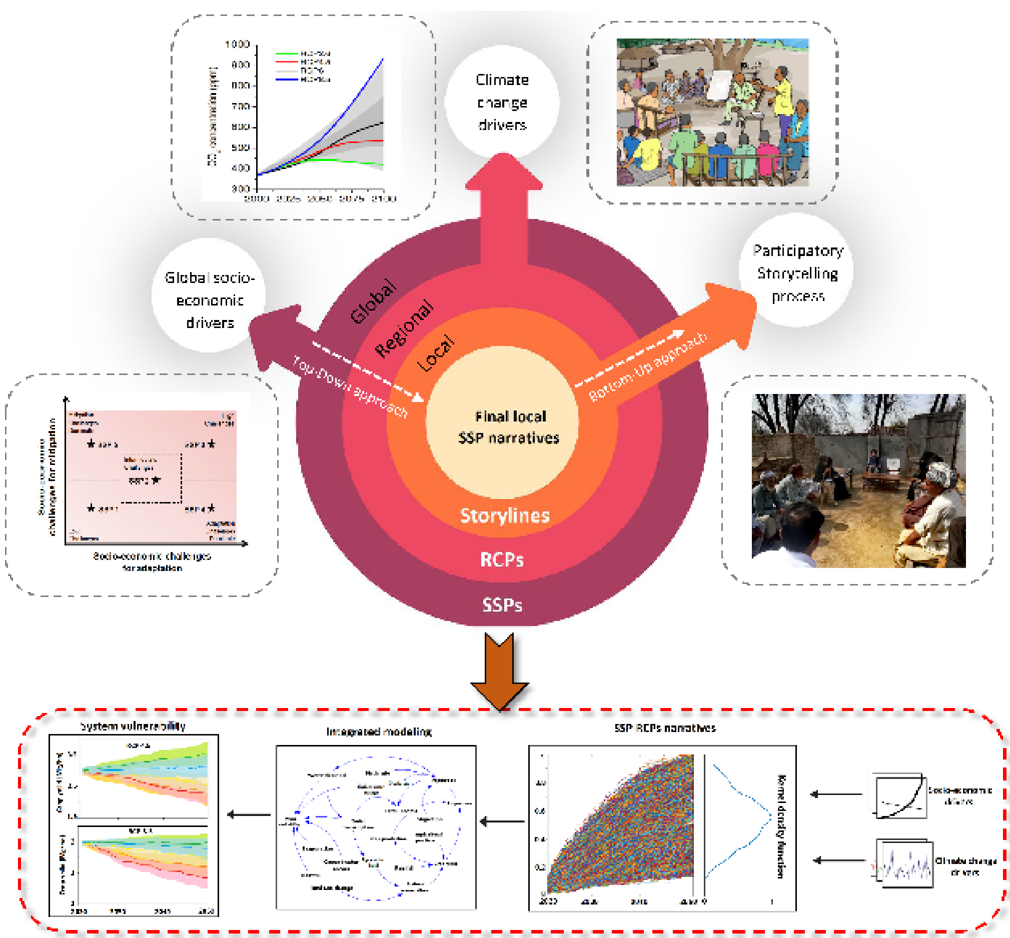

Figure 3.2 The Integrated scenario framework based on a localized hybrid SSP-RCP framework and participatory storytelling methods

3.3.1 Developing the SSP-RCP Scenario Framework

We combined SSPs for socio-economic change and RCPs for climate change to represent temporally varying socio-economic and climate systems through an ensemble of SSP-RCP scenarios. The SSPs consider five future scenarios with varying changes to population, the economy (Riahi et al., 2017), and land use (Popp et al., 2017). The SSPs provide a range of pathways for adapting to and mitigating climate change from a variety of perspectives within society (Kriegler et al., 2012; O'Neill et al., 2014;2016). In contrast, the RCPs are projections of future greenhouse gas (GHG) emissions under different end-of-century socio-economic projections (Van Vuuren et al., 2011). A series of future global warming scenarios were derived using SSPs and RCPs to integrate necessary socio-economic assumptions with future radiative forcing pathways to address future global warming. SSP scenarios were then compared to narratives generated by stakeholders in order to discern the differences between each SSP's adaptation and mitigation strategies. Societal factors that affect SSPs include demographics, infrastructure development, economic development, governance, technological advancement, and policy orientation (O'Neill et al., 2014). Generally, these factors are presented as narratives that depict change paradigms. We then considered a subset of factors (e.g., population, GDP, farm income, urbanization, and environmental consciousness) as quantitative region-specific projections. The selection of variables was based on their widespread usage, analyses of impacts, as well as the nature of their relationship. The SSP-RCPs demonstrate how society and climate can develop over future decades, providing a framework for integrated assessments.

3.3.2 Downscaling SSP-RCP Scenarios to a Local Scale Based on Narrative Storylines

We developed a participatory storytelling approach to gather narrative storylines and scenarios from stakeholders. Storytelling is a highly effective technique for describing and imagining situations to communicate information (Hazeleger et al., 2015; Zscheischler et al., 2018). Telling stories facilitates the understanding of different perspectives and provides deeper knowledge about a system, enhances conceptualization, determines relationships and uncertainties, and describes probable future possibilities among individuals from various domains and backgrounds (Booth et al., 2016; Moezzia et al., 2017; Alizadeh et al., 2020). During the storytelling process, local stakeholders participated in different activities (e.g., workshops, semi-interviews) to produce a variety of climatic and economic narratives. Section 3 of the supplementary material contains comprehensive information on stakeholders and the participatory process. We engaged different stakeholders using a five-step participatory methodological framework (Inam et al., 2015; Halbe et al., 2018; Perroneet al., 2020) that included: (i) problem definition, (ii) stakeholder analysis, (iii) interviews and causal loop diagram (CLD) development, (iv) building group CLDs, and (v) simplifying the merged CLDs model. As a means of increasing the usability of the local SSPs, we concentrated on the narratives since these clearly described the assumptions behind each scenario and facilitated their communication to a variety of stakeholders. We followed exploratory scenario development (Alcamo & Henrichs, 2008; Rounsevell & Metzger, 2010) to extract local SSPs. Emphasis was placed on the plausibility of the narratives for local adaptation planning and was evaluated on the basis of the logic and plausibility of stakeholder descriptions of the developments described in their narratives, as a function of their prospects and expectations of what may happen (Voros, 2003; Alizadeh et al., 2021). Our local SSPs explored developments up to 2050 to correspond to the global SSP time horizon. Unlike larger-scale biophysical processes, local scale processes, like human responses, generally follow shorter time scales. Therefore, policy choices and narrative scenarios were elaborated based entirely on stakeholder input for use over the next 30 years (up to 2050). As the time scale decreases, scenario assumptions become less complicated, and the corresponding results become more focused. Developing scenarios relied on these assumptions.

Following an approach employed previously (see e.g., Nilsson et al., 2017; Kebede et al., 2018; Frame et al., 2018; Mitter et al., 2019; Pedde et al., 2021), top-down and bottom-up principles were integrated by using the global SSPs as boundary conditions in our scenario development approach. Scenario development began from a top-down perspective, with regional/local SSPs based on the central characteristics of the global SSPs. There are 23 main elements identified as important in socio-economic development at the global level (Table 3.1). Important elements specifically relevant to the Rechna Doab region were carefully chosen and then complemented with local elements that were important current drivers of socio-economic development in the region's human-water system. A review of relevant case study literature was undertaken to identify relevant key elements as well as local SSP elements (Inam et al., 2015; Inam et al., 2017a, b). Based on data from local and regional administrations and statistics offices [i.e., International Water Management Institute (IWMI), Directorate of Land Reclamation (DLR), Soil Monitoring Organization (SMO), Punjab Irrigation Department (PID), Water and Power Development Authority (WAPDA), Pakistan Meteorological Department (PMD) and Water and Soil Investigating Division (WASID)], the current characteristics of local SSP elements were analyzed to form the basis of downscaled and localized SSP narratives.

Drawing on narratives and trend indicators, we followed the one-to-one mapping method of Zurek and Henrichs (2007) to map the global SSP narratives onto the local narrative scenarios. The regional participatory scenarios differ from the SSPs in some principal forms. While the SSPs were developed by a cross-disciplinary research team, our regional narrative scenarios were prepared by a collaborative group of local stakeholders. However, the most important factor is content when it comes to connecting scenarios. Mapping was undertaken between narrative scenarios and global SSPs, e.g., GDP per capita from the narrative scenarios and population and GDP growth per capita from the SSP scenarios. As a first step in the process of mapping, the values of the drivers of each SSP were analyzed. In addition, trend indicators were used as a means of updating and shifting values between both sets of narratives and SSPs. By describing how SSP elements change over time (i.e., low/high increases, low/high decreases), changes in socio-economic development during the mid-21st century (up to 2050) were determined. This gave local stakeholders a better idea of how these changes would evolve. In the process, a table was created listing all local SSP elements (For an example, see Table 3.A.1), as well as the characteristics of each local SSP.

Following this analysis, socio-economic drivers associated with global SSP elements were derived on the basis of information from the table. Local elements were further categorized into five global SSP elements (i.e., demographics, economy, policies and institutions, technology, and environment and natural resources) (For an example, see Table 3.A.2). In a final step, a full-text narrative was extracted from each local SSP (see supplementary material, Section 2). In so doing, local SSPs remained consistent with the global ones, since they were adapted so as to reflect changes at the local level, as well as socio-economic context based on the current characteristics of the local SSPs. The storytelling narrative provided perspective on local elements, thereby enhancing stakeholders' understanding. After receiving feedback from stakeholders, we revised the local SSP elements. In developing local SSPs processes, we took into account the five quality criteria as identified by Kok and van Vliet (2011): (i) the scenarios are relevant for stakeholder needs (relevance), (ii) stakeholders generally accept scenarios as plausible (credibility), (iii) stakeholder perspectives are considered in scenarios (legitimacy), (iv) future scenarios challenge current perspectives (creativity), and (v) internal consistency and rationality are maintained throughout the scenarios (structure).

Section 4.1 provides a brief overview of extracted local SSP narratives, their components, and a summary of their characteristics.

3.3.3 Regional Integrated Socio-Economic and Environmental System Dynamic Model (ISESD)

The regional integrated socio-economic and environmental system dynamic model (ISESD) represents the socio-economic and climate conditions of the human-water system. To explore a complex human-water system, the regional ISESD model integrates the major characteristics of climate, hydrology, land use, agriculture, economy and society. The regional ISESD model is based on a coupled Physical-Group-Built System Dynamics Model (P-GBSDM) built by Inam, Adamowski, and Malard (Inam et al., 2017a,b; Malard et al., 2017) in the first phase of our project.

It is suitable for the analysis of complex socio-economic changes and serves in determining policy options for climate change mitigation and adaption in the context of an integrated assessment. The model contains four main components (modules): environmental, socio-economic, water and policy analysis. The environmental module estimates agronomic data (cropping area, intensity, and duration) and water consumption (demand, conjunctive use, and leaching). The socio-economics module represents macroeconomic systems commonly used in agricultural economics. Within this submodule, outputs such as loans, income, and expenses are analyzed. Modules in the water category include irrigation application, groundwater abstraction, and a surface water storage model. The policy analysis module examines stakeholders' management and adaptation policy options during the participatory modeling phase. Various levels of financial and environmental constraints are also considered. The main modules and their subsystem modules (e.g., agricultural, domestic and industrial water demands, canal linings, seepage, effective rainfall, storage of surface water, groundwater abstraction, efficiency of irrigation application, and farm income) are interconnected through mutual feedbacks to form a holistic representation of the human-water system (Inam et al., 2017 a,b; Malard et al., 2017). Furthermore, the integrated socio-economic system dynamic model incorporates important social factors (e.g., population, GDP, rate of technological change, environmental consciousness, and social behavior). A regional modeling approach is used and the underlying processes, regardless of their socio-economic or physical nature, are considered at the regional scale. Model components exhibit a spatially-distributed behavior when computing simulated values. For each module or sub-module, the model specifies the dynamics of the individual system elements. The individual modules of the regional ISESD model are interconnected through mathematical feedbacks to identify the important dynamics of the human-water system at the intersectoral level. This form of the ISESD dynamic model offers several advantages: (i) the behavioural dynamics of the human-water system and the complex relationships between its various elements are examined; (ii) a variety of social and environmental factors are included and (iii) it is user friendly and easily understandable by stakeholders, a factor key to achieving stakeholders' engagement in decision-making and adaptation policymaking (Carper et al., 2021).

This regional integrated model was used to simulate several plausible future scenarios with localized narratives derived from stakeholders (localized SSP-RCPs). The framework was designed to provide quantitative insights into socio-economic and climate scenarios and to demonstrate the possibilities for policymaking by stakeholders using such models. As an example, Figure 3.3 displays some of the components of submodules of the regional ISESD model.

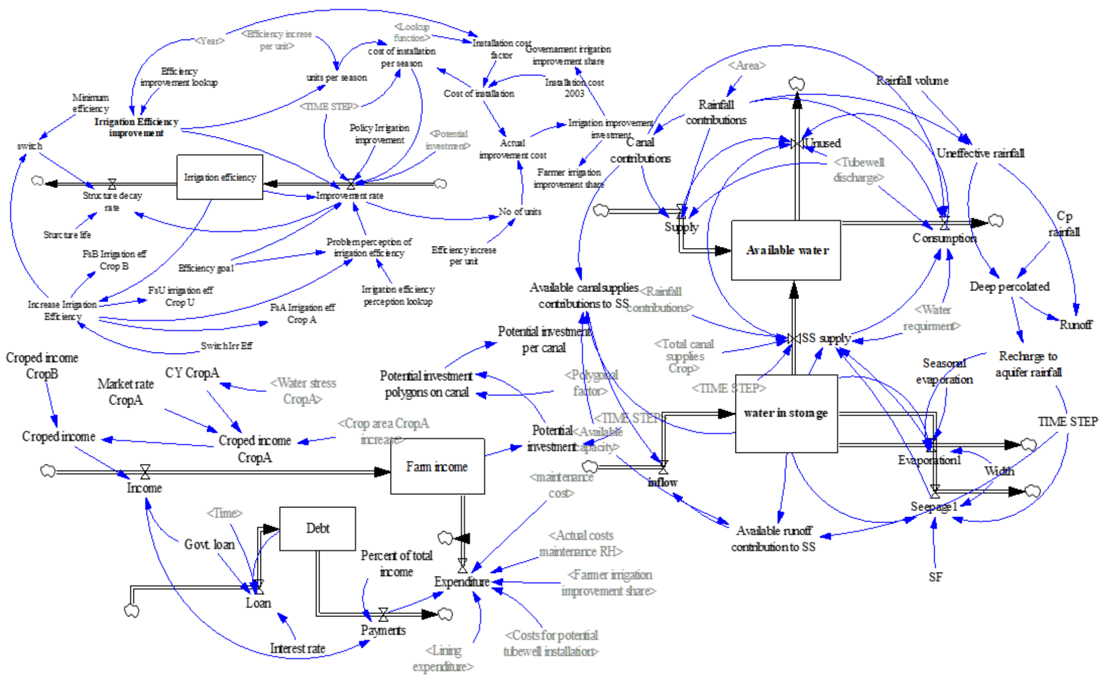

Figure 3.3 The integrated socio-economic and environmental system dynamic (ISESD) model structure

3.4 Results

3.4.1 Local SSP Narratives

Five local SSP narratives were finalized for the human-water system in the Rechna Doab region. An interactive and structured participatory process with the identified key stakeholders expanded upon the basic global SSPs and served to elicit five semi-quantitative scenarios for the human-water system in the Rechna Doab region. The storylines were analyzed according to the quality criteria (plausibility, consistency, salience, legitimacy, richness and creativity) defined by Mitter et al. (2019). The five narratives describe potential socio-economic development in the area up to 2050. To give an overview of the local SSPs, we provide the main idea and trends of each narrative (For an example see Table 3.A.1). Table 3.1 shows a summary of all local SSP elements mentioned in the narratives along with a summary of their characteristics. According to stakeholder narratives, we modified the characteristics based on O'Neill et al. (2016) to satisfy the local conditions in Rechna Doab that serve to distinguish between global SSP elements and the elements established locally.

Table 3.1 Storyline elements and trend changes of the localized SSPs grouped by provided classification as in the global SSPs.

Category	Localized SSP1	Localized SSP2	Localized SSP3	Localized SSP4	Localized SSP5
Demographics					
Population growth	+	-	--	0	++
Urbanization (level, type)	++	0	-	0	+
Human development					
Environmental consciousness	++	-	-	0	+
Societal participation	++	-	--	+	++
Local infrastructure development	++	-	-	0	+
Economy & lifestyle					
Economic model					
GDP growth (per capita)	++	-	--	0	+
Market inflation	+	++	++	+	+
Agricultural economy	++	-	--	0	++
Potential investment in agriculture	++	-	-	+	0
Consumption and demands					
Consumption and demands in agricultural	0	++	++	+	+
Domestic and Industrial demands	0	+	++	++	+
Costs and prices					
Potential operational and maintenance cost in agriculture sector	+	++	++	++	+
Relative prices for agricultural products	++	0	0	+	++
Relative prices for natural resources (*e.g.*, water, gas)	+	++	++	++	+
Policies & institutions					
Political stability	++	--	--	-	+
Multilevel cooperation	+	-	--	0	+

Institutional participation	+	-	--	+	+
Socio-environmental focus of agricultural policies	+	--	--	-	0
Implementation of adaptation measures	+	--	--	0	-
Technology					
Technology development	++	0	-	+	+
Agricultural tech. improvment	++	-	--	+	+
Environment & natural resources					
Depletion of resources	0	++	++	+	+
Efficiency of resource usage	+	--	--	+	0

A comparative description of the local SSPs according to their mitigation and adaptation challenges is provided below:

Localized SSP1:

The human-water system moves quickly toward sustainable development, with a high adaptation capacity as a key feature. A highly environmentally aware system, it consumes few resources, and prioritizes natural resource conservation. With stronger environmental policies and rapid changes in technology, economies and environmental conditions become more sustainable. Mitigation and adaptation face few challenges, and adaptation strategies cover a wide range of approaches. By focusing on environmentally friendly and sustainable policies and practices such as conservation of natural resources (e.g., groundwater) and local ecosystems, the application of adaptation measures is considered as an efficient approach that prevents additional environmental degradation (e.g., soil salinity).

Localized SSP2:

Human-water system socio-economic development follows historical patterns. The human-water system has a low adaptive capacity because of high consumption and moderate technological change. Both demand and consumption are rapidly increasing, and technology does not improve on its own. Local infrastructure is not showing significant improvement, and immense resource consumption results in the degradation of the environment. Rather than focusing on fundamental measures, imperfect adaptation actions are selected due to the lack of economic support for engineered solutions.

Localized SSP3:

The system is unresponsive to environmental and institutional issues, interactions are inefficient and technological advances slow, leading to greater mitigation and adaptation challenges. There is a high demand for local resources. In general, opportunities for participation and social cohesion are limited due to low levels of public engagement. The area lacks a robust infrastructure and technology is dated. The system expects excessive environmental degradation. Policies to mitigate climate change are inadequately developed and adaptation is not seen as necessary.

Localized SSP4:

Conflicts and confrontations increase, leading to social and environmental discrimination. Moderate economic growth is observed. Minor agricultural communities benefit from policies that support their economic growth and development. In practice, however, decisions are made in a way that ignores the preferences of the majority of the public. The agriculture sector benefits from technology development. The area's natural resources remain largely overused despite the decreasing pressure on its ecological system. Thus, despite moderate adaptation capacity, climate change mitigation is only moderately followed.

Localized SSP5:

Substantial investments are made in local infrastructure, resulting in high economic growth and societal development and providing remarkable adaptability. Local decision-making becomes more inclusive and socially cohesive as a result of effective cooperation between national and local institutions. Rapid technological advancement occurs in the system. Political initiatives geared toward reducing environmental degradation are referred to as environmental politics. There is, however, a lack of interest in climate change mitigation.

After developing the five localized SSP scenarios and as part of the participatory practice, stakeholders provided their ideas about how future changes might impact Rechna Doab economically, environmentally, or socially. Based on exchange-of-views exercises during workshops, participants identified which issues they felt were most important, with reference to elements discussed in the SSPs. Presented in accordance with the global SSPs, Figure 3.4 displays the relative importance of each local SSP element, as assessed by the stakeholders. While environmental and natural resource issues, including climate change, were the most prominent, other issues were also highlighted, especially economics, policies, and institutions.

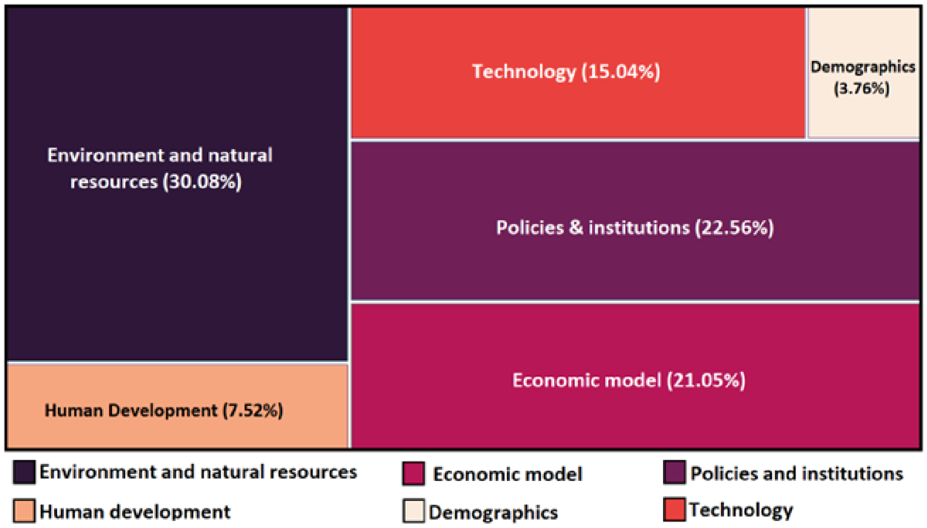

Figure 3.4 Relative importance of each element of local SSPs, based on stakeholder opinions

3.4.2 Aspects of Future Changes

Given our interest in how climate change and socio-economic changes might impact the human-water system in the mid-century period (up to 2050), we assessed the impacts of plausible future SSP-RCP scenarios on different important variables (e.g., crop yields, farm income, water demands and groundwater depletion) potentially subject to change between now and 2050 due to climate and socio-economic factors (e.g., changes in population, GDP, technology, and environmental awareness). This is described in the localized narrative SSP scenarios (see Section 4.1 and Table 3.1; Table 3.A.1 in the supplementary material). As these factors grow over this time period, they will play a major role in long-term changes in water demand, prices, and supply in such regions, especially in developing countries. The use of the regional integrated model developed in this study to simulate combinations of SSP-RCPs, allowed us to consider the effects, up to 2050, of different climate and socio-economic drivers in the presence of climate change. The results of these analyses are discussed in the following sections.

3.4.2.1 Projected Impacts on Crop Yields

Detailed production projections for rice and wheat were undertaken because: (i) Pakistan's primary food crop is wheat, supplying important quantities of protein and energy; rice represents the second largest food crop in the Pakistani diet; (ii) rice is exported much more heavily than wheat and analyzing its impact on trade can illustrate the importance of trade policy and (iii) other crops are represented by a changing mix of crops, complicating projections.

Even minor changes in climate can influence crop production in arid and semiarid regions like the Rechna Doab watershed. The assessment of future (up to 2050) plausible SSP-RCP scenarios on rice and wheat yields shows high levels of variation both within and across time periods for these two major crops (Figure 3.5). Results suggest climate and socio-economic change impacts on crop yields up to 2050 are uncertain in terms of possible decreases and increases, as well as possible changes resulting from various combinations of SSPs and RCPs. Assessing the yield projections using the SSP-RCP scenarios in the regional integrated model show that there will be a decrease in yields in three of the five cases: -1.7%, -10.37% and 16.19% under the localized SSP4, SSP2 and SSP3, respectively (Figure 3.5A). In contrast, under localized narratives SSP1 and SSP5, increases in rice yield of +22.8%, and +13.02%, respectively, are forecast. Under RCP 4.5, there is little decrease in rice yield during the mid-century compared to RCP 8.5. Based on the simulations made with the integrated model, rice is highly sensitive to increased climate change variations, and crop yields may be severely affected by the increased temperatures prevailing under RCP 8.5. The mid-century period will likely see a significant reduction in crop yields, with a 36.25% projected reduction under the SSP3 scenario. Similarly, the mid-century yield reductions are projected to be 27.25%, 23.82% and 13.43% for SSP2, SSP4 and SSP5, respectively. A slight increase of 0.55% in crop yield is predicted for SSP1 by 2050. Thus, a corresponding adaptation action would be that rice cultivation be done cautiously, and new varieties developed that are tolerant to heat and salinity.

Under RCP 4.5 and compared to current yields, wheat yield showed significant decreases of 24.53%, 26.14% and 14.84%, respectively, for localized SSP3, SSP2 and SSP4 scenarios, by the mid-century period. However, over the same period, wheat yields are projected to rise by 5.08% and 19.3% under localized SSP5 and SSP1 scenarios, respectively (Figure 3.5B). Under RCP 4.5, the relative change in yield displayed the same pattern, with all scenarios showing a decline.

According to many projections of crop yields in the area, rice and wheat yields may suffer from changes in the growing season; wheat production may be positively or negatively affected depending on the climate zone. The negative effects of climate change can be offset by some adaptative measures, including implementing enhanced research and development for higher yielding crop varieties, changing sowing dates, and using water more efficiently (Sultana et al., 2009; Yu et al., 2013; Zhu et al., 2013; Ahmad et al., 2015; Gorst et al., 2015).

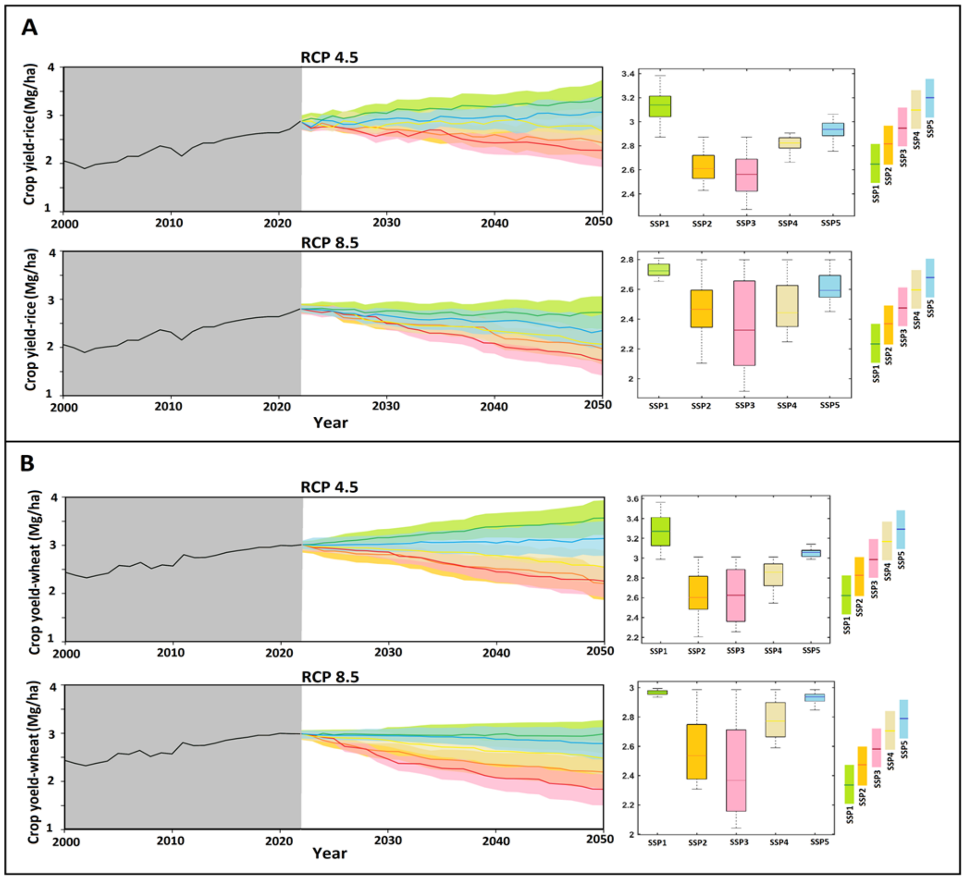

Figure 3.5 Projected changes in crop yields under different SSP-RCPs

To explore the effects of macro drivers of localized SSP-RCPs scenarios on economic and environmental outcomes, SSP-RCPs future scenarios were modeled using the regional integrated model for 30-year simulations from the base year of 2020. Figure 3.6 shows the relative (2030 vs. 2020, and 2050 vs. 2020) changes in farm income for the region under different SSP-RCP scenarios. Under RCP 4.5, for SSP1, farm income increases by 35.8% by 2050, contributing significantly to the economy. This rise in farm income is 28.9% under RCP 8.5 (Figure 3.6). Productivity and yield increases are crucial for progress in all sectors. Increasing agricultural productivity and a rise in commodity prices leads to greater farm incomes. In the case of the localized narrative SSP2 to SSP5 scenarios, farm income increased by 15.2%, 12.4%, 16.7 and 26.2%, respectively. Under the RCP 8.5, farm income did not rise significantly during the mid-century compared across the SSP2 to SSP4 scenarios. It has been the Government's tradition to provide loans to small farmers to increase their benefits and promote sustainable farming. In light of these projections, the most significant reform would be a transition to high value agriculture, which would significantly increase farm incomes and employment in the area. In response, resources should be transferred from ineffective subsidies to support farmers in producing higher value crops (e.g., vegetables, oilseeds), for which the demand is many times greater than that for lower value crops.

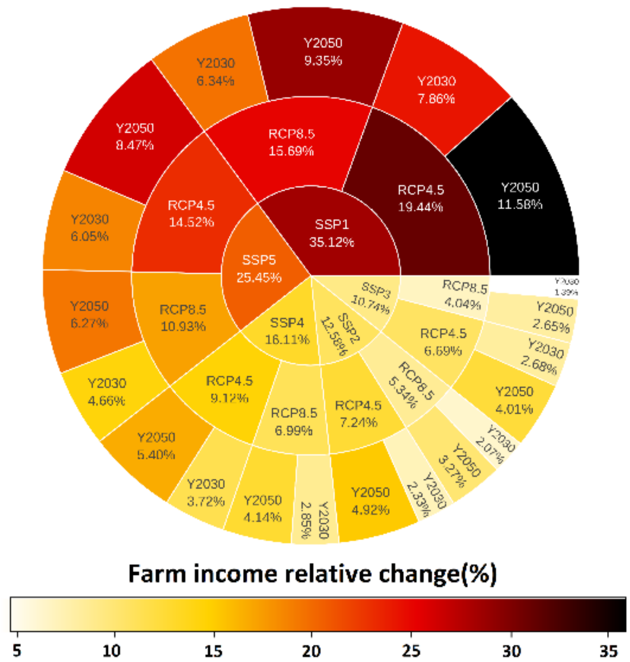

Figure 3.6 Relative change of farm income under different SSP-RCP scenarios

3.4.2.2 Projected Impacts on Water Demands

Figure 3.7A shows the quantity of water demand in billion cubic meters (BCM) for the area, under different local SSP-RCP scenarios. Climate and socio-economic changes are expected to increase water demand in the area. Climate warming's greatest impact is on agricultural water needs. A warmer climate increases evapotranspiration, resulting in increased crop water requirements, as well as increased natural water loss through evapotranspiration in the landscape. Water availability, both present and future, has a clear impact on agricultural cropping patterns. Despite significant investment in irrigation efficiency improvements and technological developments in water conservation technologies forecast to occur under some of SSP scenarios (e.g., SSP1, SSP5, SSP4), it will be difficult to meet such increased water demands with the present form of agriculture.

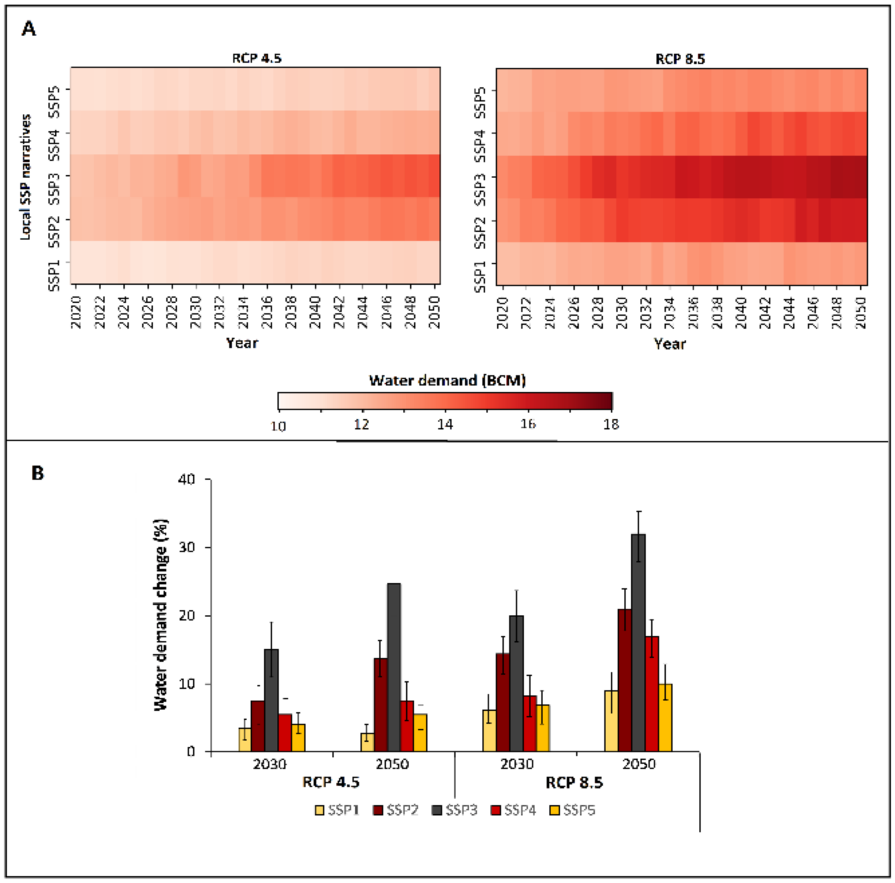

Figure 3.7 Water demands increase under local hybrid SSP-RCPs scenarios

Under the faster warming scenario of RCP 8.5, water demand could increase by more than 32.8% by 2050 for the SSP3 narrative and by 9.7%, 21.6%, 17.3% and 13.4%, respectively, for the localized SSP1, SSP2, SSP4 and SSP5 narratives (Figure 3.7B). Agricultural water demand will principally increase as a result of increased irrigation demand, which dominates overall water use in the sector. Under all socio-economic conditions, climate change is likely to increase water use, although to what extent is uncertain. Under RCP 4.5, the average projected increase in water demand in 2030 will be about 7.32% for all SSP scenarios narratives, and 10.82% by mid-century. Based on RCP projections regarding temperature and precipitation, the area stands to suffer from water shortages for the maintenance of its agriculture.

3.4.2.3 Projected Impacts on Groundwater Resources

The region's human-water system relies heavily on groundwater, which is tightly coupled to surface water. This area is highly dependent on irrigation, relying mostly on groundwater pumping. Up to mid-century, the groundwater levels will decline significantly in the area, and will be strongly influenced by the pace of climate warming and the level of socio-economic change under different SSP-RCPs (Figure 3.8A). Under RCP 8.5, severe groundwater depletion will be evident in most parts of the region, especially in the Lahore and Punjab areas. With groundwater depletion on the rise in many areas of the region, several environmental risks may arise (e.g., salinization) and will need to be addressed. This trend contributes to groundwater contamination and soil salinity, which poses a threat to long-term sustainability, especially in Punjab.

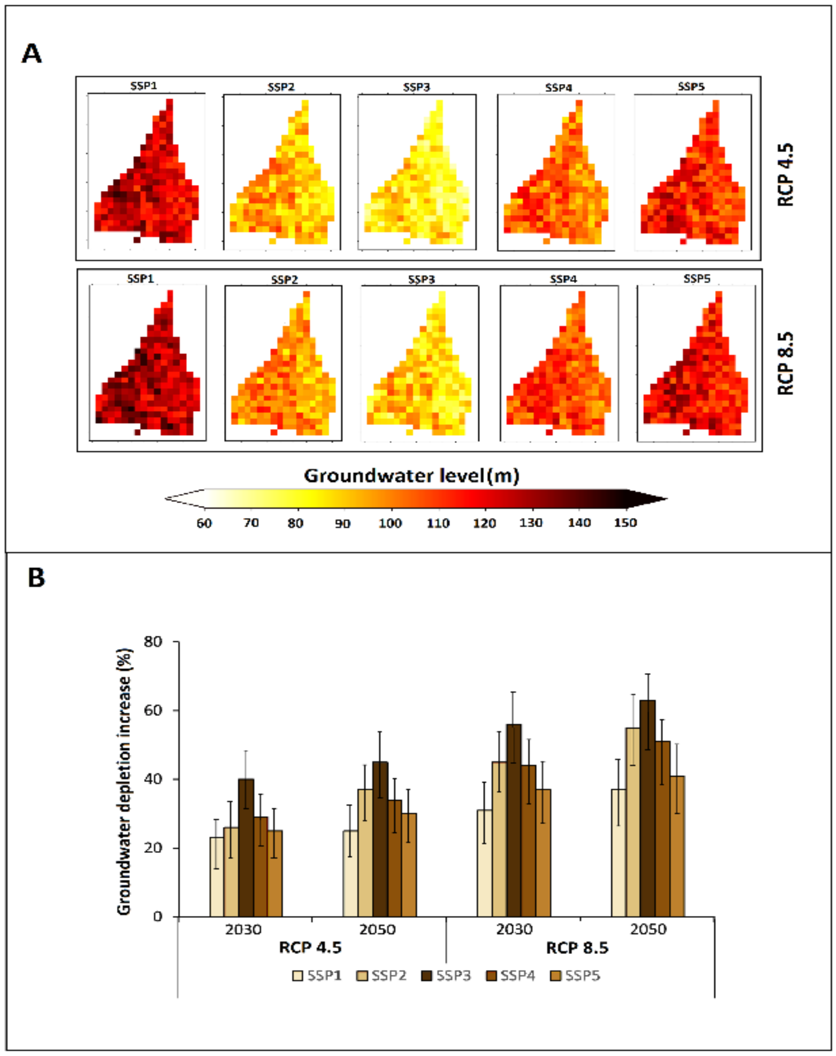

Figure 3.8 Spatial changes in groundwater level in the Rechna Doab basin under SSP-RCPs scenarios by 2050

Under different climate change and socio-economic scenarios, groundwater depletion would worsen by 2030 and mid-century periods (Figure 3.8B). Under RCP 4.5 and until 2030, groundwater use varies significantly across SSPs in response to changing socio-economic conditions of the human-water system which results in an average increase of about 29.06% for all SSPs. Under a faster warming climate, there is a larger increase with the same pattern up to 2050, because the maximum available groundwater is used each year.

3.5 Discussion

By combining top-down and bottom-up approaches, we developed five semi-quantitative local SSP scenarios for the human-water systems of the Rechna Doab region of Pakistan. Global SSPs were used as a basis for developing localized SSPs using local narrative storylines SSPs and providing a regional interpretation. The basic concepts of the localized SSPs are summarized in Table 3.1. As a result of the SSP-RCP framework employed, both mitigation and adaptation challenges, as well as SSP elements, played a key role in the development of local SSPs. The framework proposed in this study demonstrated how incorporating global SSPs based on using climate scenarios as boundary conditions under different local conditions can help generate deep and practical determinations for formulating local extended SSPs. Results of an integrated model operating under different SSP-RCPs scenarios clearly showed that the Rechna Doab human-water system is not water secure. According to the projections based on some local SSP scenarios (SSP1, SSP5, SSP4), with slightly greater rates of technological improvement (particularly in the agricultural sector), along with better policies, institutions, and environmental awareness, only slight increases in farm income and crop yields are likely. However, given the growing population, changing consumption patterns and the shift toward a growing economy that relies on cultivation, water demands will likely continue to be a major challenge. Accordingly, under different SSPs, and especially under SSP3 and SSP2, water security would decline, environmental degradation (e.g., soil salinity) would worsen, and groundwater depletion would increase. Under such scenarios, including higher global warming rates (RCP 8.5), the water sector's resilience would decline, making it more susceptible to shocks.

This set of localized scenarios illustrated future change by challenging conventional thinking about environmental resource use, helping to raise awareness about possible futures (Berkhout & Hertin, 2002; Reimann et al., 2021). In fact, during scenario workshops local stakeholders realized that a range of plausible scenarios could occur in their region. The strategic planning and scenario development processes allowed local stakeholders to understand what conditions may result in a particular desirable outcome and how to achieve this outcome. Consequently, local stakeholders were more enthusiastic about taking action (Ozkaynak & Rodríguez-Labajos, 2010; Kebede et al., 2018). This effect was particularly evident in our scenario workshops, where stakeholders discussed what they determined to be the worst-case scenario (the local SSP3 narrative) and developed ideas for adaptation if such a scenario occurred.

In the participatory workshops, stakeholders reviewed the results of plausible futures for the human-water system under a range of SSP-RCP scenarios and several high-level recommendations regarding how to improve adaptation policies in Rechna Doab were produced. Stakeholders recommended linking management of water resources to local policy outcomes, institutional performances, infrastructure, and economies. The goal of increasing economic growth (SSP1, SSP5) by 2050 will require multiple reforms and investments over the next decades. A major improvement in water productivity is needed in agriculture. The agricultural sector and other users will need to reallocate a significant proportion of the water that is currently used for irrigation to other purposes including infrastructure, environment and industrial development. According to the proposed SSP-RCP framework, the most complex adaptation needs occurred under SSP3, SSP2 and SSP4 and under a faster rate of global warming (RCP 8.5). Rechna Doab is therefore facing challenges in the development of these scenarios, which are becoming increasingly urgent. The political and economic challenges explored by SSPs make improving water management, in particular improving the efficiency of irrigation, drainage and cropping systems, extremely challenging. Investing in environmentally-friendly technologies (e.g., precision farming) and seeking to reach soil sustainability by improving irrigation, drainage and cropping systems should be considered. As part of better governance, there must also be strong, multi-level cooperation with regards to local and national sectors, including environmental, agricultural, and social issues. The establishment of a multi-stakeholder planning process is another important priority for the long-term sustainable management of water resources in the region. There are many problems with the current water distribution, irrigation, and farming systems, including the fact that they do not provide economic efficiency, are not flexible enough to cope with future changes in water demand, and do not adequately adopt an environmental sustainability approach. To improve environmental sustainability, local stakeholders and authorities need to improve their connections. Presently, adaptation planning is mainly focused on major infrastructure projects, which are heavily influenced by the government. To inform future planning, a multi-stakeholder process is required and diverse non-governmental organizations (NGOs) representing water users and interest groups should be involved in this effort.

We have tried to contemplate a few drawbacks and challenges related to localized SSP scenarios. During the development of the storyline, we expended considerable efforts to involve stakeholders so as to include heterogeneous perspectives and make the process more comprehensive. However, some issues remain which may constrain the legitimacy, consistency, and creative ability of the narrative storylines. First, it was difficult to gather a diverse range of perspectives from all stakeholders. In our effort to engage stakeholders, we took into account the perspectives of those who lacked the resources, or who were unwilling to undertake the multi-step process of using the storytelling method. Furthermore, participant-driven interdisciplinary storyline development has some limitations in terms of reproducibility and explicability for identifying relationships between important uncertainties and the behavior of stakeholders (Carlsen et al., 2017; Reimann et al., 2021). To ensure that major conclusions were robust, we followed the recommendations of Wright et al. (2013), regarding the organization and documentation of stakeholder interviews. In the same vein, we faced challenges matching stakeholder offerings to the storyline and potential directions for change that we did not always agree on (Frame et al., 2018; Kunseler et al., 2015). Additionally, stakeholders often focused on specific aspects of individual storylines and avoided addressing the bigger picture. Local stakeholders' participation and background knowledge were crucial factors in shaping stakeholder narratives. Given that stakeholders had diverging perceptions and different educational backgrounds (Biggs et al., 2007; Reed et al., 2013), it was difficult at times for them to imagine plausible future developments until 2050. It was also difficult to convince them that the scenarios explored possible futures, rather than predicting what would happen.

In this study, we pointed out the strengths and weaknesses of the storytelling, emphasizing its potential to engage participatory stakeholder engagement in climate adaptation for coupled human-water systems, as well as raising awareness of future challenges. Despite its potential to develop in terms of stakeholder engagement, storytelling proved to be an effective and straightforward way for transitioning from global to local narratives (Alcamo, 2008; Kok and van Vliet, 2011). As a result of this technique, stakeholder values are highlighted in analyses of coupled human-water systems since stakeholder values could be used to generate meaningful scales without requiring additional assumptions. It also facilitates communication and understanding between modeler- and stakeholder-led communities and integrates qualitative and quantitative methodologies using multiple uncertainty concepts.

3.6 Conclusions

In this study, we developed a set of five localized SSPs for the Rechna Doab watershed in Pakistan, which served as a case study of a typical human-water system in a developing country, by employing storytelling methods to establish a narrative scenario development process combining a multi-scale (top-down) and a co-production (bottom-up) approach. These projections were combined with climate scenarios (RCPs) to provide insight into plausible future impacts of socio-economic and climate change and the effectiveness of different adaptation measures. This can provide information useful in guiding local adaptation actions. To assess the implications of climate and socio-economic changes, we analyzed local narratives together with the projections. Our developed localized narrative SSPs provided the basis for exploring the potential impacts of socio-economic and climate change at a local scale, under a wide range of socio-economic futures. Moreover, the narratives provided a basis for downscaling projections of important processes and variables such as population growth and economic developments. These projections were used to simulate and quantify local impacts on social and environmental factors of the human-water system (e.g., farm income, crop yields, water demands and groundwater resource depletion). By analyzing the local SSP narratives using a regional integrated assessment model, significant future changes in these important socio-economic and environmental variables could be forecast, helping decision-makers to explore and develop appropriate policy interventions and adaptation strategies. Local SSPs play a crucial role in the development of adaptation planning for the region based on what is identified by local stakeholders as an important climate service. We illustrated the advantages of using a hybrid multi-dimensional scenario framework to understand diverse change causes. The framework emphasized the need to incorporate stakeholder perspectives. The local SSPs also contributed significantly to a better understanding of the socio-economic conditions in the study area, by raising awareness among local stakeholders. The idea, methodologies, and procedures are adaptable to different sub-national and regional contexts confronted with multi-scale challenges. The proposed framework can provide a suitable foundation for policy making of future adaptations that takes into account regional and local planning, as well as socio-economic conditions.

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Appendix

Throughout this Supplementary Material, the final, comprehensive storylines for local SSPs will be explained. Based on defined elements of global SSPs, each storyline contains five major elements: population and urbanization, economy, policies and institutions, technology, and environment and natural resources.

3.A.1 Section 1:

Workshops and semi-structured interviews were conducted to engage different groups of stakeholders in developing the SSPs. Semi-quantitative scenarios were generated through a structured and interactive participatory process. During a workshop, the first draft of SSP1 (Table 3.A.1) was discussed with respect to its structure, length, and thematic focus and it is provided to give an overview of the local SSPs. The stakeholder groups generally considered the outline useful but decided to shorten storylines, including drivers of human-water systems, exclude impacts of plausible future developments, and strengthen stakeholder engagement.

Table 3.A.1 The full narrative storyline for Rechna Doab watershed human-water system extracted in the participatory process.

Draft 1. First full SSP1 storyline narrative extracted for Rechna Doab watershed.
Economic stability is seen as the key to development in the Rechna Doab watershed and is accompanied by moderate but constant growth. Agricultural productivity and land productivity are major contributors to economic growth and employment opportunities in the agriculture sector of the area. Agriculture plays an important role in developing a sustainable and resilient economy in regions. Consequently, agriculture contributes positively to the GPD. Farm income will thus rise slightly, and income instability will decrease as a result. A farm career becomes more sustainable and offers a broader range of work opportunities. In this sense, economic growth helps to improve human development and social cohesion. Different crop products in the region become more autonomous and independent as the supply and demand chain for domestic products develops. For agricultural practices to meet the strict standards set by the environmental conservation

measures, it works with other sectors such as the food industry and environmental agencies. There is a change in demand patterns in the agricultural sector. A small increase in agricultural demand follows a gradual increase in plant product demand. Because of a general increase in environmental awareness, farmers are engaged in preserving their natural ecosystems and considering nature protection. In the agricultural sector, new technologies are rapidly transmitted. As a result of such improved technology and management, crop yields and productivity increase. The use of advanced technologies benefits agricultural production (*e.g.*, double cropping, intercropping), technology improvements for irrigation systems, and the use of environmentally friendly methods such as precision farming. Additionally, water resources are used more efficiently and pollution risks are reduced by implementing sustainable practices. Agricultural commodity prices are stable and slightly decreasing due to developments in productivity and demand patterns. Due to environmental impacts, regulations, and consumption, prices of farming inputs such as pesticides, fertilizers, and fuels are also on the rise. In spite of the growing degree of urbanization, population levels remain pretty stable. Consequently, the quality of access to social and technological infrastructure benefits society. Therefore, it promotes social and environmental sustainability as well as effective human-environment interactions and increased trust between farmers and society. Agricultural sector awareness in society has increased due to this change. In addition to increased productivity, technological progress is also accompanied by higher environmental standards. There is better interaction between authorities and organizations regarding multi-level collaboration regarding local and extra-local policies such as those related to the environment, agriculture, and society. As cooperation is increased, environmental policies becomes stricter, which regularly improves environmental awareness. The objectives of environmental policies are to reduce waste,

protect the environment, and conserve energy and resources. Thus, production and consumption are more sustainable. Prices of agricultural commodities can be kept reasonable by providing subsidies on the demand side in order to facilitate products that are good for the environment. A significant contribution to agricultural technology advancement comes from private investment. Therefore, new agricultural technology becomes more environmentally friendly, and resources are used more efficiently through green farming, soil conservation, and effective water use. A growing environmental consciousness, investment in sustainable management, and technological innovation are driving factors for more efficient use of natural resources. The result is a decrease in resource depletion and the struggle of different sectors to find resources.

Table 3.A.2 summarizes the local SSP1 elements mentioned in the narratives, along with a summary of their characteristics. Adapted from O'Neill et al., (2017), we modified the characteristics distinguishing between global SSP elements and those established locally in Rechna Doab.

Table 3.A.2 Modified SSP1 narrative storylines based on five socio-economic elements of global SSPs.

Draft 2. First full SSP1 storyline narrative extracted for the Rechna Doab watershed. Demographics ■ Economy ■ Policies and institutions ■ Technology ■ Environment ■
Economic stability is seen as the key to development in the Rechna Doab watershed and is accompanied by moderate but constant growth. Agricultural productivity and land productivity are major contributors to economic growth and employment opportunities in the agriculture sector of the area. Agriculture plays an important role in developing a sustainable and resilient economy in regions. Consequently, agriculture contributes positively to the GPD. Farm income will thus rise slightly, and income instability will decrease as a result. A farm career becomes more sustainable and offers a broader range of

work opportunities. In this sense, economic growth helps to improve human development and social cohesion. Different crop products in the region become more autonomous and independent as the supply and demand chain for domestic products develops. For agricultural practices to meet the strict standards set by the environmental conservation measure, it works with other sectors such as the food industry and environmental agencies. There is a change in demand patterns in the agricultural sector. A small increase in agricultural demand follows a gradual increase in plant product demand. Because of a general increase in environmental awareness, farmers are engaged in preserving their natural ecosystems and considering nature protection. In the agricultural sector, new technologies are rapidly transmitted. As a result of such improved technology and management, crop yields and productivity increase. Agricultural production is benefited by the use of advanced technologies *(e.g.,* double cropping, intercropping), technology improvements for irrigation systems, and the use of environmentally friendly methods, such as precision farming. Additionally, water resources are used more efficiently, and pollution risks are reduced through the implementation of sustainable practices. Agricultural commodity prices are stable and slightly decreasing due to developments in productivity and demand patterns. Due to environmental impacts, regulations, and consumption, prices for agricultural inputs such as pesticides, fertilizers, and fuels are also on the rise.

In spite of the growing degree of urbanization, population levels remain pretty stable. Consequently, the quality of access to social and technological infrastructure benefits society. Therefore, it promotes social and environmental sustainability as well as effective human-environment interactions and increased trust between farmers and society. Agricultural sector awareness in society has increased due to this change. In addition to increased productivity, technological progress is also accompanied by higher environmental standards.

There is better interaction between authorities and organizations with regards to multi-level collaboration regarding local and extra-local policies such as those related to the environment, agriculture, and society. As cooperation is increased, the number of environmental policies becomes stricter, which regularly improves environmental awareness. The objectives of environmental policies are to reduce waste, protect the environment, and conserve energy and resources. Thus, production and consumption are more sustainable. Prices of agricultural commodities can be kept reasonable by providing subsidies on the demand side in order to facilitate products that are good for the environment. A significant contribution to agricultural technology advancements comes from private investment. Therefore, new agricultural technology becomes more environmentally friendly, and resources are used more efficiently through green farming, soil conservation, and effective water use. A growing environmental consciousness, investment in sustainable management, and technological innovation are driving factors for more efficient use of natural resources. The result is a decrease in resource depletion and the struggle of different sectors to find resources.

3.A.2 Section 2:

Here we provide an overview of all socio-economic elements of the local SSP narrative storylines developed through participative activities. The following includes a full description of the principal features of the narrative, as well as a comparison of the local SSP and the global SSP based on mitigation and adaptation challenges. Five local SSPs were developed during the study:

3.A.2.1 Localized SSP1 Narrative:

Demographics:

In the Rechna Doab watershed human-water system, the population remains almost constant even though the area's degree of urbanization is on the rise. The growth of the population is considered constant with a stable trend. Better access to technical and social infrastructure, therefore, benefits society. Because of a general increase in environmental awareness, farmers are engaged in preserving their natural ecosystems and considering nature protection.

Economy:

Employment and economic growth are both driven by the agricultural sector. Through this contribution, the region's economy can be transformed into a more sustainable and resilient economy. There is a modest increase in farm income and a decrease in farm insecurity. Human development and social cohesion are supported by economic growth. Agricultural demand patterns are changing in the sector. A slight decrease in agricultural commodity prices can be attributed to improvements in agricultural productivity and demand patterns. A rising trend in agricultural input prices is also seen because of environmental impact regulations and increased consumption. Sustainability is becoming more important in production and consumption. Agricultural commodities have price increases that are regulated by demand subsidies which protect the environment and human health.

Policies and Institutions:

Multilevel cooperation with involved authorities and organizations is more efficient when it comes to dealing with local and extra-local issues such as environmental, agricultural, and societal policies. As cooperation is increased, the number of environmental policies becomes stricter, which regularly improves environmental awareness. Different crop products in the region become more autonomous and independent as the supply and demand chain for domestic products develops. By doing so, a shift occurs towards a more sustainable social and environmental system that promotes effective interactions between farmers and society as a human-environment system and increases trust. Consequently, the agricultural sector is viewed positively in society as a result of this change.

Technology:

In the agricultural sector, new technologies are rapidly transmitted. As a result of such improved technology and management, crop yields and productivity increase. The use of advanced technologies benefits agricultural production (e.g., double cropping, intercropping), technology improvements for irrigation systems, and the use of environmentally friendly methods, such as precision farming. The advancement of technology also increases productivity, but gains are limited by the high standards for the environment. Modifications and advances in agricultural technology are largely due to public and private investments. The outcome is agricultural technology is more environmentally friendly, and resources are used efficiently by using green farming, soil conservation, and water conservation.

Environment and natural resources:

In order to comply with the strict environmental regulations, the agricultural sector works directly with other sectors, such as the food industry and environmental agencies. As the overall demand for agricultural products increases, so does the demand for plant products. Resources are used efficiently in environmental policies, nature is protected, energy is saved, waste levels are reduced, and environmental damage is reduced. For more efficient use of natural resources, environmental awareness, investments in sustainability management, and technology development are the main drivers. In other words, resource depletion declines while different sectors struggle to get enough resources.

3.A.2.2 Localized SSP2 Narrative:

Demographics:

Despite the constant population growth, the trend remains the same. Environmental awareness increases as a result of an increase in general education. The agricultural sector is experiencing an increase in societal interest in environmental responsibility. The socio-economic status of farmers does not appear to be improving too much.

Economy:

Moderate growth continues in the economy. As education levels rise and health awareness increases, demand patterns are slowly changing. Plant-based and agricultural products are in high demand. Agriculture inputs, as well as commodities, continue to be stable in terms of price and volatility. Natural resources such as land and water are becoming more expensive as a result of a continuous decline in their quality and quantity from various sectors, including agriculture. Because of the slow but continuous progress in technology standards, operational and maintenance costs in the agriculture sector are slowly increasing.

Policies and Institutions:

There are conflicts of interest among authorities and organizations in the private and public sectors that prevent practical cooperation, resulting in slow social and environmental improvement and an ineffective course of action. However, policy-making in agriculture follows a gradual process, which involves balancing different and conflicting goals such as maximizing productivity and preserving the environment.

Technology:

In the agricultural sector, new technologies are transmitted slowly but continuously at a moderate pace. By increasing resource efficiency, including improvements to irrigation systems and to the use of environmentally friendly technologies applied to pesticides, fertilizers, fuel, and water usage, this gradual technology development is designed to promote sustainable development and reduce production costs.

Environment and Natural Resources:

There is an increase in resource demands in various sectors, including agriculture and industry. While water use and irrigation areas increase, environmental policies do not improve as quickly. Resources such as agricultural land and water are being depleted and degraded across the region. Agricultural land productivity remains steady.

3.A.2.3 Localized SSP3 Narrative:

Population and Urbanization:

The population decreases slowly due to declining birth rates. Economic growth limits and slows down urbanization. The poor connections between rural and urban areas result from a loss of environmental awareness and consumer confidence in agricultural producers. There is a decline in public and government investment in social and technical infrastructure, resulting in weak infrastructure development and maintenance.

Economy:

Markets are limited, and economic growth rates decline. Agricultural and governmental sectors are skeptical of each other, which negatively impacts the economy. Agricultural supply chains become less transparent, and prices for agricultural inputs (such as seeds, mineral fertilizers, and pesticides) are higher due to weak democratic foundations and decreased investment in traceability systems. Agricultural commodities become more in demand due to self-sufficiency. A result of this is an increase in both input costs and commodity prices. There is an increase in the price of natural resources such as land and water due to increased demand from various sectors, including agriculture.

Policies and Institutions:

As a result of ongoing political conflicts between the various involved organizations and sectors, there is instability in the political and environmental environment, and there is a lack of cooperation among the organizations and institutions. Consequently, decision-making processes fail to integrate several stakeholders, including society.

Technology:

Because of a decrease in investment in technology development and a lack of cooperation between sectors and organizations, technology development and transmission has slowed. The slow development of technologies impedes the extension of services that can boost production efficiency. The slow pace of agriculture development and implementation is also attributed to weak cooperation among stakeholders. Additionally, stakeholders are skeptical about new technologies due to their uncertainty and potentially destructive impact.

Environment and natural resources:

The system is not primarily concerned with resource use efficiency and environmental protection. In transboundary watersheds, for instance, increasing resource pressure causes environmental conflicts to intensify. Environmental awareness is decreasing, environmental organizations are not sufficiently involved in decision-making processes, and there is reduced cooperation between different sectors, which leads to resource depletion. Environmental standards are increasing, and farming regulation and maintenance interests are decreasing due to decreasing societal concern for the environment. The system consequently lacks both the quality and quantity of resources.

3.A.2.4 Localized SSP4 Narrative:

Population and Urbanization:

A decreasing fertility rate leads to population decline. A human-water system characterized by social inconsistencies and conflicts leads to social discrimination. The relationship between the public and decision makers is deteriorating. There are also income and education inequalities in the agricultural sector.

Economy:

Moderate economic growth is observed. Minor agricultural communities benefit from policies that promote economic growth. Agricultural products have varying levels of demand, but in general, agricultural commodities are in great demand. In addition, the price of agricultural inputs is on the rise because agricultural products are becoming more competitive on the market, and the price of fuels and electricity is also going up.

Policies and Institutions:

Having more effective and improved connections with authorities and government benefits local and national organizations. In decision-making, however, a large portion of the public and society's preferences is ignored. As a result, the organizations lack public support. Cohesion and social equity are also subsiding in importance on the policy making agenda as a result of this situation. Regulations affecting the agricultural sector are losing public interest, resulting in reduced public engagement.

Technology:

In order to maintain environmental sustainability, policies support the development of technology and the appropriate implementation of environmental solutions. In the agricultural sector, technology improvements include improved irrigation systems and investments in environmentally sustainable farming practices, as well as machinery and vehicle technology. Large-scale industrial farms benefit from an enhanced fundamental change associated with increased efficiency in land and water use.

Environment and Natural Resources:

Society supports the preservation of a clean environment. Therefore, environmental standards improve, and agricultural lands and water become regulated. Natural resources and ecological infrastructure are experiencing decreasing pressure. However, the region is still severely overexploited in terms of natural resources.

3.A.2.5 Localized SSP5 Narrative:

Population and urbanization:

Increasing birth rates lead to an increase in population. There is an increase in migration from rural areas and small villages to developing cities. In the agricultural sector, people are becoming more educated and trusting of technology. As population growth increases, the system's social and technical infrastructure develops rapidly. Society has become more aware of environmental issues, along with infrastructure, economic assets, and the environment.

Economy:

The economy is strengthening rapidly as a result of increased investments in technological development. In the agricultural industry, quality standards have increased, increasing demand for agricultural commodities. The changing prices of agricultural commodities and the decreasing fuel costs are associated with a decrease in the relative prices of agricultural inputs. Technological advances and improved management increase agricultural productivity and the economy.

Policies and Institutions:

Economic growth and reducing interinstitutional conflicts are the goals of organizations and agencies. A multilevel collaborative approach in economic, environmental, and development policy encourages faster development. As a result, environmental objectives are being postponed due to the priority of economic growth.

Technology:

Increasing innovation increased investment in development, and decreased fuel prices have contributed to rapid technological progress toward high productivity. To improve agricultural productivity and speed up processing, many agricultural procedures are automated. Improvements in soil management, farm management techniques and irrigation systems are all advancing rapidly. The agricultural machinery and structure industries have made significant technical advances.

Environment and Natural Resources:

Resources are used intensively as demand increases. As a result, land, water, and ecosystems are under increasing pressure. Furthermore, the pressure on natural resources is increasing. As environmental awareness decreases, more environmental problems are a result of careless use and missing environmental policies.

3.A.3 Section 3

3.A.3.1 Stakeholders Identification

The watershed's primary stakeholders were identified and categorized in order to invite them to our workshops for the purpose of creating our participatory local SSPs and ensuring that the model accurately represented watershed dynamics. Stakeholders were selected based on their impact or involvement in watershed modeling, implementation, or decision-making processes, as well as their knowledge and capacity for data collection. Stakeholders from various organizations were asked to participate in the development of participatory local SSPs based on their desire and technical competence. The following table outlines the key stakeholders identified for the creation of the local SSPs.

Table 3.A.2 Overview of the key stakeholders for the local SSP development process.

Category	stakeholder
Authorities	• International Water Logging and Salinity Research Institute (IWASRI) • Land Reclamation Department • Soil Salinity Research Institute • Agriculture Department
Decision Makers	• Water and Power Development Authority (WAPDA) • Punjab Irrigation Department

	• Ministry of Agriculture and Livestock • Local Governments • Area Water Boards
Implementers	• Agriculture Engineering Department • Water Management Department • Environmental Protection Agency
Consumers	• Local Farmers • Domestic Consumers • Farmer Organizations

3.A.3.2 Participatory Workshops Planning Preparation

Two workshops involving the research team (3 researchers) and engaged stakeholders (18 stakeholders for workshop 1 and 23 stakeholders for workshop 2) were held during the field study to enhance communication and preparedness. Stakeholders were informed of their anticipated roles and responsibilities, and all relevant documents (model descriptions, data, global SSP elements) were made available for review and discussion. Workshop meetings were held in neutral, third-party venues to reduce distractions and to guarantee the full involvement and availability of all workshop planning session participants.

Table 3.A.3 Format of the stakeholder's workshop during the local SSP development process.

8:30 am – 9:00 am	• Greetings and introductions • Aims and goals of the workshop • Outline and agenda • Introduction to the day's activities
9:00 am – 10:30 am	• Socio-economic trends and forecasts of SSPs • Presentation of sample trends from the model and full discussion • Assessment of socio-economic impacts • Developing plausible scenarios

	• Identify policy choices
10:30 am – 11 am	• Break
11:00 am – 12:30 pm	• Climate change trends and projections • Presentation of sample trends from model and the entire discussion • Developing plausible scenarios • Identify policy choices
12:30 pm – 1:00 pm	• Break
1:00 pm – 2:30 pm	• Workshop evaluation and closing comments • Review, identification, and evaluation of SSPs, strategies, and coping mechanisms • Group presentations on local SSPs and narratives • Group discussion • Comments and suggestions about the workshop • Reflecting on the day

3.A.3.3 Design of Key Questions

Stakeholders were given three primary questions on the stories and local SSP scenarios:

- What if...? What kind of local effects are possible in a scenario of socio-economic and climatic change and development? Can we evaluate the implications of different combinations of socio-economic and climate change factors, as well as local development decisions, in the absence of perfect clarity about future conditions?
- So what? Do the consequences of socio-economic transformation scenarios matter? When stakeholders such as farmers, irrigation distributors, water resource planners are presented with these effects, the discussion may shift to whether or not the identified impacts affect their vision of the future. Could the long-term effects of socio-economic and environmental change jeopardize attempts to achieve local development goals?

- Is there anything that can be done? How can the study area's development priorities be defined? What metrics of adaptability should be considered?

The following are some samples of questions in Urdu (the area's official language):

- کیا معاشرہ حالیہ برسوں کے بارے میں مطمئن ہے؟
- مستقبل کس طرح نظر آئے گا؟
- کیا ہم آب و ہوا کو تبدیل کرنے کی توقع رکھتے ہیں اور اگر ایسا ہے تو کیا شرح اور شدت کے ساتھ؟
- ہمیں کونسا پانی کی انتظامی حکمت عملی چاہیئے؟
- موجودہ حکومت کی پالیسیوں کو نظام کو کس طرح متاثر کر رہی ہے؟
- مجھے لگتا ہے کہ پانی کی کمی کی وجہ سے مستقبل میں زیادہ شدید ہو جائے گا؟
- حکومت کو کسانوں کی مدد کرنا چاہئے؟
- اگر میرا فصل پیداوار فی ہیکٹر فی 10 ٹن سے کم ہو؟
- میں اپنی فصل کی قسم تبدیل کروں گا؟
- میں اپنا کام تبدیل کروں گا؟
- حکومت آپ کے لئے کیا کر سکتا ہے کہ آپ زیادہ زمینی استعمال نہیں کرتے ہیں؟

3.A.4 Section 4

Pictures of the storyline narratives from a participatory storytelling scenario workshop (Photos: Azhar Inam):

Figure 3.A.1 Extracting the storylines for possible futures with farmers

Figure 3.A.2 Group discussion of the narratives

Figure 3.A.3 Discussing and revising developed scenarios with stakeholders

CONNECTING TEXT TO CHAPTER 4

The localized SSP-RCPs scenario framework, developed in Chapter 3 based on storyline narratives of stakeholders, aids in the development of an integrated perspective on regional socio-environmental and climate changes, but also contains inherent deep uncertainty when used in the context of integrated modeling of coupled human-water systems. Although these scenarios are helpful for adaptation policy design at regional scales, they suffer from different types of uncertainty.

Therefore, in this chapter quantitative methods of scenario analysis are applied to these local storylines to represent uncertainty in complex human-water systems. This chapter is based on uncertainty quantification of localized /downscaled scenarios from the previous phase of the study, and focuses on a transdisciplinary approach that integrates social and environmental sciences to characterize and comprehend uncertainty in the dynamic interactions of key factors affecting a human-water system. A framework for representing uncertainty through linguistic and epistemic uncertainty quantification using storyline narratives in the context of a regional integrated dynamic model is discussed in detail.

This chapter is under review in the Journal of Hydrology (Alizadeh, M.R., Adamowski, J. and Inam, A., 2022. Scenario analysis of local storylines to represent uncertainty in complex human-water systems. Journal of Hydrology). The format has been modified to be consistent within this thesis. All literature cited in this chapter is referenced at the end of this chapter.

The author of the thesis was responsible for the development, testing, and application of the different methods and wrote the manuscript presented here. Prof. Adamowski, the supervisor of this thesis, provided valuable advice on all aspects of the research and contributed to the review and editing of the manuscript. Dr. Azhar Inam, Assistant Professor in the Department of Agricultural Engineering at Bahauddin Zakariya University in Pakistan, helped with review and editing of the manuscript.

CHAPTER 4: Scenario analysis of Local Storylines to Represent Uncertainty in Complex Human-Water Systems

Mohammad Reza Alizadeh, Jan Adamowski, Azhar Inam

Abstract

Storylines are important in evaluating the uncertainty inherent in complex human-water systems. The interrelated nature of qualitative and quantitative scenarios can enhance the ability to address the uncertainty of integrated modelling of complex systems. This study proposes a transdisciplinary approach that integrates social and environmental sciences to characterize and comprehend uncertainty in the dynamic interactions of key factors affecting a human-water system. We introduce a framework for representing uncertainty through linguistic and epistemic uncertainty quantification using storyline narratives in the context of a regional integrated dynamic model. A systematic exploration of uncertainty space is performed using storytelling, fuzzy sets, and low discrepancy sequences sampling methods. Scenario analysis is applied to the generated uncertain ensemble of projections to discover predominant storylines of interest. As a representative case of a human-water system operating in a developing country, we examine the uncertainty effects of a variety of drivers of climatic and socio-economic changes on key agriculture and water-related sectors in Pakistan's Rechna Doab region. The findings revealed soil salinity and crop yield indices were the most uncertain and showed significant variance across all developed storylines. The 95th percentile for soil salinity in year 2100 was estimated to be nearly 60% higher than the baseline level (year 2020). There was, however, considerable overlap in different socio-economic scenarios at the local scale, indicating that change in socio-economic conditions could not fully offset climate-related uncertainty. Our analysis provides better quantification and a deeper understanding of the uncertainty in integrated assessment modelling of the coupled human-water system and the complex relationships between inputs and outcomes.

Keywords: Scenario analysis, Uncertainty, Integrated dynamic models, Storyline narratives, human-water systems, Participatory modelling

4.1 Introduction

The interaction between humans and water is traditionally described as a coupled system, with complex and unpredictable dynamics, and non-linear connections since human and natural forces are mutually reinforcing (Elshafei et al., 2014; Di Baldassarre et al., 2016; Konar et al., 2019). The coupled or complex systems approach is based on the assumption that social and environmental system interactions can be described in a highly synthetic and unpredictable fashion, which calls for an integrated method for analyzing and studying these systems (Nuno et al., 2014; Ropero et al., 2016). However, considerable uncertainty regarding the magnitude and impact of future climate changes and unpredictable socio-economic conditions introduce ambiguity into these complex human and environmental systems (Kasprzyk et al., 2013; Brown et al., 2015; Giuliani et al., 2016; Herman et al., 2020). Furthermore, since these systems are extensively interconnected, any uncertainty within them may be exacerbated as a result of their interactions (Dawson et al., 2011; Brown et al., 2015). Many of the interactions between human and environmental systems are therefore uncertain, complicated, and poorly understood (Sivapalan et al., 2014; Herman et al., 2020). The deterministic view of causal linkages in complex environmental and socio-economic systems ignores the uncertainties and varying aspects of intrinsic causality. Cause-and-effect relationships alone are unable to depict the complexity associated with real-world interdependence. Due to the many sources of these uncertainties and their possible consequences and implications, developing sustainable policies may be challenging without a very defined quantification framework. The extent of these uncertainties, however, must be precisely estimated given that the consequences of climate change are highly dependent on actions and adaptation plans that depend on these estimations. Although most human-water systems research has focused on conceptualizing indicator frameworks to quantify uncertainty, attempts to construct models using real-world studies and incorporating uncertainty communication at finer scales (i.e., regional and local) are essential. Integrating qualitative and quantitative scenarios has been identified as a promising tool in solving complex challenges (Alcamo et al., 2008; Refsgaard et al., 2016) and has been popular in scenario production (Vermeulen et al., 2013; O'Neill et al., 2020).

Complementary methods including storytelling are emerging that provide a more detailed exploration of inherent interconnections and degrees of uncertainty in complex human and environmental systems. In contrast to quantitative linear causal connections or probabilities, the narrative style focuses on qualitative comprehension (Bou Nassar et al., 2021). More importantly, a focus is placed on comprehending the underlying reasons for changes and evaluating their plausibility. The narratives in human-water systems frequently relate to socio-economic and climatic changes, with the uncertainty centered around human perspectives and the future. Listening to stakeholders describe socio-economic or environmental interactions using their local language provides an in-depth examination of underlying relationships and uncertainty levels as their perspectives are a reflection of their historical knowledge, areas of expertise and observation. (Hazeleger et al., 2015; Shepherd et al., 2018). The storyline method expresses and communicates uncertainty related to socio-economic and climate change in ways that are pertinent to specific policymaking and enforcement of policy measures (Hazeleger et al., 2015; Dessai et al., 2018; Alizadeh et al., 2020). There are a number of applications of stories, narratives, and scenarios in the climate change literature (e.g., Haasnoot et al., 2015; Döll and Romero-Lankao, 2017), and analyzing such narratives has allowed researchers to explore how policymaker discourses and stakeholder discussions frame climate change (Thompson et al., 2013). Stories are therefore, a powerful way of connecting socio-economic and climatic change in human-water systems because they dominate the conversation when considering the human component (Rasmussen, 2005; Wu et al., 2016; Dessai et al., 2018). In this study, we used storylines to represent and address the uncertainty of socio-economic and climate change factors that influence human-water systems, taking into account past and future events.

The purpose of this research is to propose a novel framework that integrates qualitative storytelling approaches with probability-based simulations of low discrepancy sequences sampling and scenario discovery methods to characterize and understand the uncertainty in important socio-environmental outcomes in integrated dynamic models. Specifically, this study provides insight into how to quantify uncertainties and vulnerabilities by using an effective participatory analysis of storyline narratives under scenario discovery of different plausible future projections. We show how storytelling narratives can be utilized to derive probability distributions for uncertain socio-environmental drivers. Furthermore, by combining storylines and quantitative scenario techniques, we discover potential policy-relevant narratives for exploring the outcome of interest. We draw on stakeholders' experiences to generate narrative storylines and convey the uncertainty and dynamic interconnections between socio-environmental drivers in a complex human-water system. We pose the following questions: 1) Using stakeholders' narratives, how can we develop probability distributions of uncertain socio-environmental drivers in a complex human-water system? 2) In what ways can an integrated socio-economic and environmental model effectively yield insights into the uncertainties and vulnerabilities of a complex human-water system? 3) Are there prevalent narratives that demonstrate a significant relationship between the desired outcome (e.g., farm income) and the other outcomes of the integrated dynamic model? We explore these issues in the context of Pakistan's Rechna Doab region, a complex human-water system with multiple stakeholders.

An Integrated Socio-economic and Environmental System Dynamics (ISESD) model developed with stakeholders (Malard et al., 2017; Alizadeh et al., 2022) is used to support and test a framework to quantify the uncertainty of human-water system under a range of socio-economic and climate changes processes. Using probability-based sampling from each integrated model's input variables, we quantify and analyze the uncertainty of desired outputs of the integrated model to represent uncertainty in the narrative storylines. In the storylines, past and future events are included in a way that emphasize the uncertainty and plausibility of driving variables. Various possible futures are represented in the storylines developed by the stakeholders although for the sake of this study, we keep the different futures to a reasonable number. Furthermore, we develop an ensemble of scenarios based on derived computational experiments of local storylines and run the integrated dynamic model to quantify the uncertainty in model outcomes and elaborate on their possibilities. Finally, a different application of scenario discovery techniques is applied to uncertainty ensembles to explore the relationship between farm income and other outcomes and to discover cohesive storylines of interest. The proposed methodology facilitates understanding the complexities inherent in a highly uncertain and dynamic relationship between the environment and society. Specifically, the proposed novel framework contributes to the following objectives: (i) investigate the plausibility boundary from an uncertainty perspective by using storylines; (ii) expand the credibility of a regional integrated dynamic model as a basis for exploring uncertainties; (iii) identify coherent storylines in an ensemble of uncertainties by exploring the diversity of outcomes; and (iv) engage stakeholders in an event-oriented, as opposed to a probabilistic way, of exploring uncertainty, which better reflects how people perceive and react to future events.

4.2 Study Area

This study focused on a heavily irrigated part of the Rechna Doab watershed in central-northeastern Pakistan (Figure 4.1), which has a large human-water nexus. This is a large watershed in Pakistan's section of the Indus Plain, covering about 732.5 km2 in the interfluvial basin of the Ravi and Chenab rivers (latitude 30°32'-31°08'N, longitude 72°14'-71°49'E). It consists of one of the world's largest contiguous irrigation systems (Ahmad, 2002; Inam et al., 2017a, b). As there is a shortage of surface water, farmers heavily rely on groundwater to irrigate their crops (Arshad et al., 2019). A lengthy, hot season extends from April to September with temperatures ranging from 21 to 49˚ C. The winter season lasts about three months with maximum temperatures between 25 to 27°C (Ahmad, 2002; Inam et al., 2017a, b). Rice and cotton are the most important summer crops, while wheat and forage are important winter crops. Rechna Doab has a wide variety of socio-economic and environmental challenges related to water resource management, due to the involvement of numerous stakeholders (see Supplementary Material, Table 4.A.4). As a result, it provided an interesting opportunity to compare, test, and evaluate the proposed framework's effectiveness.

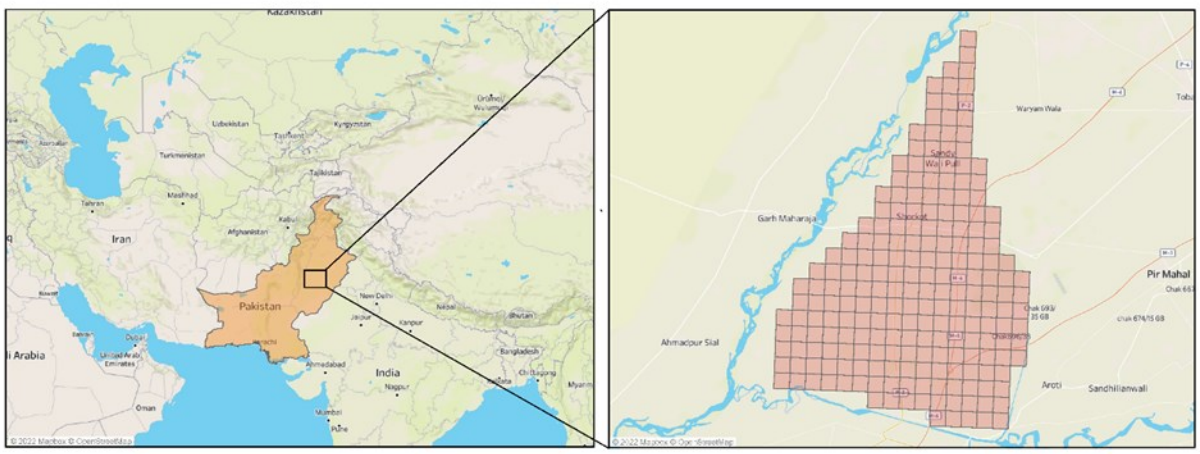

Figure 4.1 Study area in Pakistan’s Rechna Doab basin.

4.3 Methods

The proposed framework included the following steps: (1) Develop storyline narratives with stakeholders in a participatory manner; (2) Quantify vagueness of the main uncertain parameters in each storyline and identify distributions; (3) Sample probabilistic parameters to measure from the distributions; (4) Generate an ensemble of model runs for each storyline using simulation with the integrated dynamic model; and (5) Carry out scenario analysis of uncertain ensembles to discover outcomes of interest. The overall approach to scenario analysis of storyline narratives for representing uncertainty is depicted in Figure 4.2. The four pillars of the proposed framework in this study are:

- A storytelling approach through participatory analysis to extract uncertainties in both the physical and societal parts of the human-water system and create narrative storylines;
- Fuzzy sets methodology combined with a low discrepancy sequences method, a resampling procedure to generate probability distribution functions of model parameterizations and systematic parameter uncertainty space exploration.
- An integrated Socio-economic and Environmental System Dynamic (ISESD) model to evaluate the human-water system uncertainties using narrative storylines and stakeholder-defined ranges.

- Scenario discovery techniques to explore if there are prevailing storylines behind outcomes of interest.

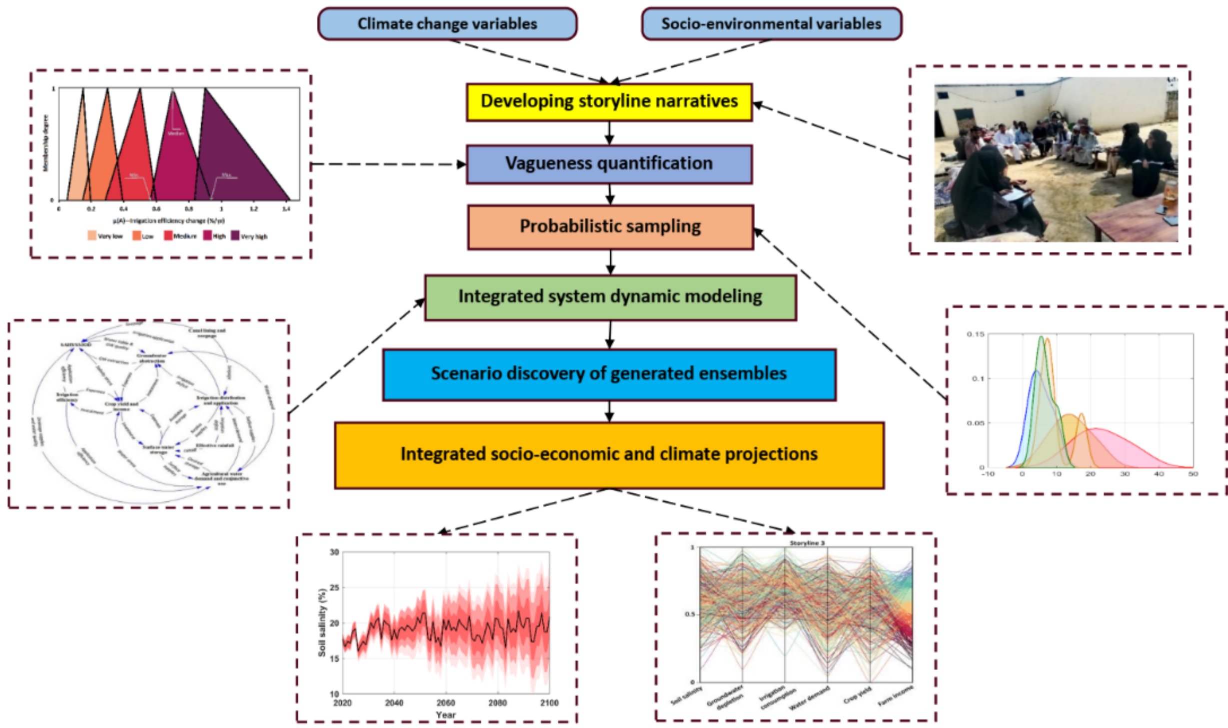

Figure 4.2 Framework for developing storylines with stakeholders and their uncertainty quantification with the integrated model.

During the participatory modelling activities, the storyline development process was applied to capture narrative storylines from stakeholders about socio-economic and climate change drivers. The storylines provided the context for understanding uncertainties, dynamic interactions of future socio-economic and climate change at a regional scale in the considered human-water system. The narrative storylines were aimed to inform inputs to the Integrated Socio-economic and Environmental System Dynamics (ISESD) model (see Section 3.1), using uncertainty ranges of model inputs from stakeholder input and the scenario default values. We took into account both linguistic and epistemic uncertainty due to limited data and stakeholder knowledge (van Vliet et al., 2010; Mallampalli et al., 2016) when interpreting the quantifications derived from stakeholder input. The ranges from stakeholders' inputs were intended to reflect the epistemic uncertainty associated with the quantities described, and the fuzzy-set and probabilistic interpretation were intended to represent the linguistic uncertainty.

4.3.1 Integrated Socio-economic and Environmental System Dynamics (ISESD) model

The ISESD model is designed to explore the cross-sectoral impacts of climatic and socio-economic factors and the potential for adaptation to mitigate or eliminate any vulnerabilities that may accompany them at a local scale. The model consists of two main components: a physically-based model to simulate the agricultural and hydrological processes of the water system (e.g., groundwater, soil salinity, crop yield, etc.) and a system dynamics model to simulate the human system (e.g., population, income, awareness, etc.). The system dynamics model to simulate human behavior was developed with stakeholders and then coupled with the physically-based simulator using the Tinamit coupling wrapper (Malard et al., 2017). The model makes use of an interactive, participatory, and system dynamics approach that provides broad sectoral insights and helps stakeholders and decision-makers acquire the capacity to address complex issues related to socio-economic and climate change impacts and trade-offs associated with various adaptation options in uncertain futures. The regional ISESD model was constructed based on a coupled Physical-Group-Built System Dynamics Model (P-GBSDM) established by Inam, Adamowski, and Malard (Inam et al., 2017a, 2017b; Malard et al., 2017; Alizadeh et al., 2022). With the ISESD model, stakeholders had access to an interactive evaluation tool developed through system dynamic modelling techniques that integrated many submodules such as agriculture, water needs, irrigation, surface water and groundwater modules (Anderson et al., 2020; Carper et al., 2021).

The ISESD's primary contribution to current knowledge is its holistic framework, which significantly advances integrated model applications in three ways: (I) increased consideration of cross-sectoral linkages and dynamic interactions by integrating four key sectors (environmental, socio-economic, water, and policies); (ii) consideration of both climatic and socio-economic factors; and (iii) incorporation of multi-scale applications (local/regional scale: combines bottom-up stakeholder insights with knowledge from the scenarios).

ISESD's uncertainty analysis attempts to quantify and describe interactions between its many components in order to better understand the potential implications of future changes in circumstance (climate change, social, economic, technical, environmental, and governance scenarios), that transcend regional scales. This indicated how various assumptions could impact decision-making and which assumptions or characteristics are crucial for determining future regional adaptation goals. Socio-environmental narratives were evaluated using the ISESD model and stakeholder inputs. By completing this assessment, stakeholders gained greater confidence and comfort with their future scenarios.

4.3.2 Narratives: Exploring Plausibility

In this study, we examined socio-economic scenarios created through participatory storytelling.

We used these scenarios to provide context for understanding uncertainties and future climate change consequences at local and regional levels. These narrative scenarios directly informed the numerical inputs to the ISESD model, which included default inputs based on stakeholder inputs that were tailored to each scenario. Stakeholder inputs were used to generate quantitative interpretations that explicitly accounted for both linguistic and epistemic uncertainty. Stakeholders provided ranges to account for epistemic uncertainty in the quantities (see Section 3.2.1), while fuzzy sets and probabilistic interpretations were utilized to account for linguistic uncertainty (Sections 3.2.2 and 3.3).

4.3.2.1 Storyline Development

Using storytelling techniques is an effective way to describe and articulate events while imparting knowledge and demonstrating ideas (Zscheischler et al., 2018; Hazeleger et al., 2015). People with diverse fields of expertise and from different social and professional backgrounds can use storytelling to facilitate mutual understanding. A storyline elicited and developed by local stakeholders can be used by researchers to gain a deeper understanding of a system, improve model conceptualization, identify uncertainty and interactions, and characterize future scenarios (Bou Nassar et al., 2021). This makes storytelling an effective tool for fostering meaningful stakeholder engagement (Alcamo, 2008; Trutnevyte et al., 2014). Narrative approaches are also ideally suited for interactive modelling exercises, since they support the investigation of non-linearities, multi-causality, and complex causal relationships. Consequently, storytelling can be used to inform and conceptualize models of human-water interactions.

In previous phases of this study (Alizadeh et al., 2022), we held two workshops as part of the participatory modelling activities where stakeholders were engaged to create narratives. As part of the narrative-development process, stakeholders identified the major and uncertain drivers predicted to have an impact on the trajectory of the socio-economic and environmental system. A thorough understanding of the key drivers of the human-water system, including environmental and socio-economic variables, was the focus of the workshops. Storylines included environmental events (e.g., droughts), trends (e.g., precipitation, temperature and economic crises) and interactions between the water system and society (e.g., mitigation measures and water scarcity impacts). To ensure a diverse range of expertise, stakeholders were selected from a variety of backgrounds and education levels (see Section 3 in Supplementary Materials). Please refer to Inam et al., (2015) and Alizadeh et al., (2022) for details on the stakeholder selection process. Participants developed all storylines through workshops that alternated between group brainstorming sessions and plenary debates, a technique known as the causal loop diagram technique (Inam et al., 2015; Halbe et al., 2018). Both narratives and key inputs were communicated in such a way that they were intrinsically linked. Participants (facilitators and stakeholders) were encouraged to work together to develop both scenarios and key input quantifications. In order to achieve consistency in the co-production of narratives and quantifications, this technique was essential.

There were three distinct phases in the workshop process. Part one involved listing, discussing, and selecting important uncertainties that affected all future scenarios, along with developing narratives. In the second part, participants discussed the narratives from part one (group exercise) and provided linguistic (qualitative) trends for important variables. The final activity involved stakeholders expressing a view as to whether numerical ranges were the best means to reflect those qualitative trends. Stakeholders contributed data ranges to predict the vulnerabilities of the human-water system based on trends in four proxies of resource availability (human, social, environmental, and financial). As a result of this qualitative input from stakeholders, we were able to quantify a wider range of socio-economic factors that we could then account for in the integrated model. Details on the narrative development process and the extraction of vagueness variables from linguistic variables can be found in the Supplementary Materials.

In order to manage shifts in stakeholder perspective over time, and uncertainty that resulted from divergent opinions among stakeholders, the perspectives technique (Offermans et al., 2011; Offermans, 2016) was used to develop scenarios and narratives. As a means of representing the potential uncertainty associated with differing perceptions between stakeholders, pessimistic and optimistic perspectives were employed. Through this approach, social and natural sciences perspectives were incorporated as a framework (Figure 4.2) to assess various alternatives in an uncertain future. Additionally, the results of a comprehensive sensitivity analysis of the ISESD model (Peng et al., 2020) were considered to substantiate the selection of the most sensitive and uncertain variables. Afterward, the ISESD model quantified and examined these uncertainties (see Section 3.2.2). Uncertain variables are listed in Table 4.2 (Section 4). For more information about the process of creating narratives with stakeholders and quantification, please see the Supplementary Materials and Alizadeh et al., (2022).

4.3.2.2 Analyzing Narrative Vagueness

The lack of linguistic exactness comes up in stakeholder-driven scenarios since different stakeholders may interpret words such as 'high/low' and 'increase/decrease,' differently in relation to various socio-economic and climate factors such as irrigation efficiency. Using trend indicators extracted from narratives, we followed the method of Brown et al., (2015) and Pedde et al. (2019) to quantify the vagueness of local narrative scenarios. Each stakeholder was asked to quantify this ambiguity by offering a quantitative range for linguistic descriptions 'high/low' or 'increase/decrease'. The ranges derived from stakeholder values varied according to the backgrounds, beliefs, and expertise of stakeholders. 'High/low' and 'increase/decrease' are ambiguous and can be analyzed mathematically using fuzzy logic (Zadeh 1975a, b). By using fuzzy numbers as a membership function, the numerical ranges offered by stakeholders could be represented (e.g., Cornelissen et al., 2001; Pedde et al., 2019;). As in Zadeh (1975a), a linguistic variable had a linguistic value, a non-numerical complement of a numerical value; an input range was used to indicate the linguistic value associated with a particular linguistic variable. For maximum clarity, linguistic and model variables had the same meaning. In other words, stakeholders were presented with the model variables (e.g., irrigation efficiency, crop intensity) and utilized linguistic variables. The value of a linguistic variable might vary. For example, a linguistic variable named 'change in irrigation efficiency', had five linguistic values from 'significant reduction' to 'significant increase' in our narrative creation technique (Section 2, Supplementary Materials). A description of linguistic variables and their associated values are shown in Figure 4.3 as an example, along with the ranges of "irrigation efficiency change" and "crop intensity" indices reported by stakeholders. In our analysis, we considered quantitative estimates of the overall uncertainty in nine indicators representing the expected changes in socio-economic and climatic conditions according to storyline development phase (see Table 4.2).

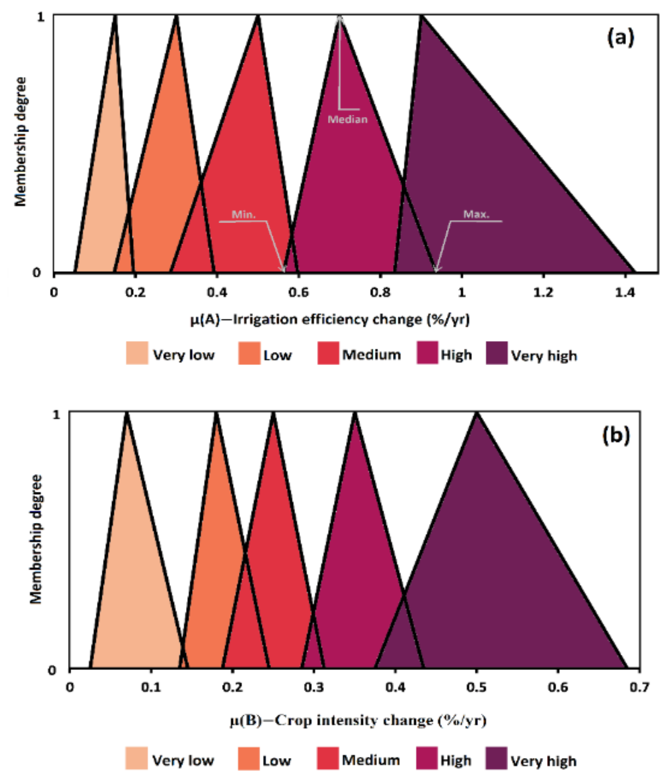

Figure 4.3 An interpretation of linguistic variables and their linguistic values based on the numerical ranges supplied by stakeholders: (a) changes in irrigation efficiency; (b) crop intensity.

Fuzzy membership functions were calculated using the linguistic data to serve as integrated model inputs. Based on their degree of association with the linguistic variable, membership functions of a linguistic variable (e.g., μ_A and μ_B) provided numerical values to each range (X). For example, as shown in Figure 4.4, the range of a linguistic variable was assumed to be contained within a space described by the median, a measure completely associated with the linguistic variable (A) ($X_{Median} = 1$), and the maximum and minimum ranges, defined entirely by the linguistic variable μ_A ($X_{Min,Max}$)= 0.

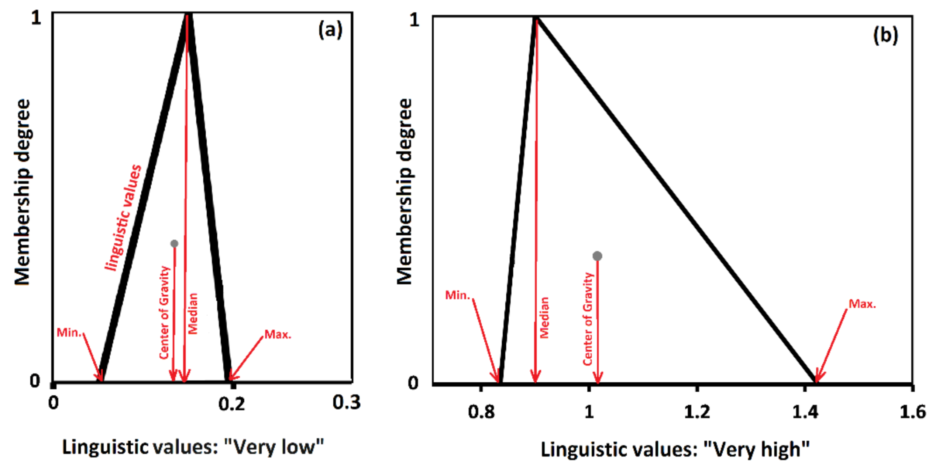

Figure 4.4 Defuzzification of the linguistic values using the center of gravity method for the linguistic variable of 'irrigation efficiency increase': (a) 'very low' and (b) 'very high' linguistic values.

A defuzzification operator was then applied to the linguistic values. We employed the Centroid Method to defuzzify linguistic values. As a result, data were defuzzifed using the center of gravity (CoG) operator (Figure 4.4), which indicated that minor changes in the input would result in modest changes in the output. Using μ_C as the continuous membership function of the linguistic variable, CoG is defined by (Leekwijck and Kerre, 1999):

$$z^* = \frac{\int \mu_C(z).z\, dz}{\int \mu_C(z) dz} \quad (4.1)$$

As an additional step (Eq. 4.2), the CoG of the membership function was calculated using the highest, lowest, and median value for each linguistic value resulting from discussions with all stakeholders (Brown et al. 2015; Pedde et al., 2019):

$$COG\ (x) = 1/3(Min + Median + Max) \quad (4.2)$$

CoG reflects the average between the lowest, median, and maximum values of a membership function and gives a more accurate forecast than the median value. As outlined earlier, using the CoG, we converted the qualitative adjustments in each scenario into quantitative adjustments. Once these quantified modifications were made, they were applied to the ISESD model.

4.3.3 Probabilistic Parameters Sampling to Measuring Vagueness

Using probability density functions developed for each model input, the integrated model quantified epistemic uncertainty and the validity of stakeholder opinions regarding future changes. For the ISESD model, input parameter values were assigned distinct (linguistic) ranges. For each linguistic variable, we specified default ranges in the 95, 90, and 85 % ranges, assuming a probability distribution for the CoG. In evaluating model and scenario uncertainty using qualitative storytelling, we were able to identify the ranges of values of input variables by using participatory storyline construction. The variable ranges (derived from stakeholder input) were based on scenario-specific data and uncertainty information. They changed over time based on the conditional values within each scenario. Under each scenario, each variable had a range of potential values. The probability density function (PDF) was generated by interpreting these ranges and values probabilistically.

As a suitable distribution for variable PDF, beta distributions were selected due to their flexibility, suitability for previous assumptions, and lack of truncation. Prior uncertainty studies have also used beta distributions (e.g., O'Hagan 1998; Heath and Smith 2000; Brown et al., 2015; O'Hagan et al., 2016), and they provide a reasonable estimate of the inherent (and unknown) uncertainty of physical processes. The parameters in each scenario were fitted with distinct distributions. The fit was constructed by using the center parameter (the mode) and the lower and upper range limits, which would include the interval [0, 1]. With the quasi-random sequence method, also known as low discrepancy sequences (Niederreiter, H., 1988; Saltelli et al., 2010), samples were extracted from each PDF for each of the narratives. The measure of uniformity in a sequence is the discrepancy of a sequence, which is defined as follows (Levy, 2002):

For every set of points $x^1, x^2, \dots, x^N \in I^s$ and a subset $G \in I^s$, identify the counting function $S_N(G)$ as the number of points $x^i \in G$. For each $x_1, x_2, \dots, C$ assuming G_x as the rectangular s - dimensional region $G_x = [0, x_1) \times [0, x_2) \times \dots \times [0, x_s)$ with $x_1, x_2, \dots, x_N$. Then the discrepancy in the points $x^1, x^2, \dots, x^n \in$ is defined as:

$$D_N^*(x^1, x^2, \dots, x^n) = sup_{x \in I^s} |S_N(G_x) - N x_1 x_2, \dots, x_s|, \tag{4.3}$$

Low-discrepancy sequence creation aims at identifying as few sequences as possible. Several sequences have been created to achieve this goal. We used Sobol quasi-random sequences (Sobol, 1976). In addition to its low computational cost, this variance-based method was selected because of its ability to generate model parameterizations that perform a systematic investigation of the uncertainty space and lack of assumptions.

4.3.4 Scenario Discovery of Narrative Storylines

Scenario discovery is a method for identifying the challenges associated with the characterization and communication of uncertainty in complex simulation models (Lempert et al., 2008; Bryant and Lempert, 2010; Kwakkel, 2017). A machine learning algorithm is used to discover outcomes of interest and their occurrence conditions from computational experiments of model simulations. Then the effects of uncertainties involved with a simulation model are analyzed to determine regions of interest in the uncertainty space (Kwakkel et al., 2010; Bankes et al., 2013). This can then inform the development of particular scenarios for deeper exploration. In complex, integrated dynamic systems with interacting complexities and many uncertainties, scenario discovery can be a beneficial tool. In the literature, scenario discovery is often applied to robust decision making as well as the analysis of input-output-based datasets by sampling input uncertain parameters. A scenario discovery process can, however, also be applied to large datasets of scenarios, such as those generated by the computational experiments of our integrated dynamic model. Using ensemble simulations to examine endogenous outcomes is a new frontier application of the scenario discovery approaches, which has recently been used by Rozenberg et al. (2014); Guivarch et al. (2016).

To investigate whether there were prevailing storylines underlying outcomes of interest, we applied scenario discovery approaches to our previously constructed probabilistic ensembles. To accomplish this, ensembles were classified according to whether they reached or did not reach the desired outcome using the Patient Rule Induction Method (PRIM) classification algorithm. Other machine learning classification techniques, including Classification and Regression Trees (CART), and logistic regression, can be used for this purpose as well (Breiman et al., 1984; Friedman & Fisher, 1999; Lempert et al., 2008). By employing this method, associations between outputs were detected as well as relevant scenarios. Following that, we identified the primary factors that influenced the desired outcomes. The scenario discovery approach also helped address one of the main shortcomings of the probabilistic analysis that each outcome be individually characterized.

4.4 Results

4.4.1 Narratives Uncertainty

In this paper, we explored the outcomes of scenario assessment in Pakistan's Rechna Doab area for a multi-stakeholder coupled human-water system. Five semi-quantitative storylines concerning the human-water system in the area were generated by an interactive and organized participatory approach involving selected relevant stakeholders (Table 4.1). Each of the five storylines highlights the area's socio-economic growth prospects through to year 2100.

Table 4.1 Summary of local narratives according to their socio-economic and environmental aspects.

Narratives	Descriptions

Storyline 1	Using few resources, natural resource conservation is prioritized. Markets and the ecosystem become more stable when environmental policies and technology change rapidly. Adaptation measures, (e.g., groundwater conservation), are considered an efficient approach to prevent further environmental degradation (e.g., soil salinization).
Storyline 2	The human water economy follows historical patterns. High consumption and moderate technological change reduce the system's adaptive capacity. The demand and consumption for technology are growing rapidly. The environment is degrading due to inadequate infrastructure and resource consumption.
Storyline 3	Insensitivity to organizational and natural resources and interactions is extended. Local resources are in high demand. Because of low levels of public engagement, participation and societal collaboration are generally limited. In addition, the technology is out of date. Environmental degradation is expected to be severe. Adaptation to climate change is not seen as a necessity.
Storyline 4	Increased conflicts result in social and environmental inequality. Economic growth is moderate. Economic policies support minor agricultural communities. Technological advances benefit agriculture. Despite diminishing pressure on the ecosystem, the region's natural resources continue to be overexploited.
Storyline 5	Infrastructure investments contribute significantly to economic and societal growth. By collaborating effectively, national and local institutions lead to more inclusive decision-making at the local level. Technology develops rapidly. Policies become focused on reducing environmental degradation.

We carefully selected characteristics unique to the Rechna Doab area, and combined them with local elements that play significant roles in the region's development and climatic change. We identified nine main socio-economic and climatic drivers at the local level (Table 4.2). Table 4.2 describes and quantifies the CoG for major socio-economic and climate drivers of the human-water system, according to the five narratives of linguistic, socio-economic, and environmental drivers found in Table 1. The CoG represented the single output of a fuzzy set for each linguistic variable, i.e., the default value of the membership function. Next, the range of possibilities including the default value was used to determine the linguistic uncertainty throughout the integrated dynamic assessment modelling processes. Generally, this was accomplished by describing the variance as a PDF, which preserved the shape and range of the stakeholders' quantification while also allowing for rigorous uncertainty analysis through parameter sampling. We provided quantitative estimates of the overall uncertainty in nine indicators characterizing the expected socio-economic and climatic changes according to the ISESD model. These metrics were chosen so as to illustrate the full spectrum of human-water system interactions and to be pertinent to policymakers and adaptation methods.

Table 4.2 Centre of gravity (CoG) for the linguistic variables of the scenario narratives.

Drivers	Storyline 1	Storyline 2	Storyline 3	Storyline 4	Storyline 5
Environmental drivers					
Temperature change (C^0 yr^{-1})	0.04	0.08	0.1	0.15	0.3
Precipitation change (% yr^{-1})	0	-0.05	-0.1	-0.25	-0.4
Socio-economic drivers					
Irrigated area growth (% yr^{-1})	0.04	0.07	0.4	0.45	0.75
Crop intensity change (% yr^{-1})	0.1	0.18	0.25	0.3	0.5
Irrigation efficiency change (% yr^{-1})	0.05	0.1	0.18	0.25	0.4
Industrial water intensity change (m^3 yr^{-1} MWh^{-1}).	2.5	1.5	0	-2.5	-3
Domestic water intensity change (L $person^{-1}$ day^{-1} yr^{-1})	-2.5	-1.5	0	0.5	1.5
Environmental consciousness	Very low	Low	Medium	High	Very high
Technology development	Very low	Low	Medium	High	Very high

4.4.2 Uncertainty Analysis

A total of 74 output metrics were generated in each integrated run at a spatial resolution of 215 individual grid cells (2.1×2.1 km in size) across the area. We focused our findings on six key measures that provided insight into the predicted impacts of socio-economic and climate changes on key agriculture and water-related sectors: soil salinity, farm income, groundwater depletion, irrigation use, crop yields, and water demand. The measures were presented at the regional level by averaging the grid-level and their uncertainty was assessed by showing their distributions. Figure 4.5 shows the PDFs for each of the measures (averaged over all storylines and simulated grid cells). The results revealed that the uncertainty level in the output measures under consideration varied widely across local narratives. Also, there were cases of multi-modality, which might be a consequence of change due to situations or patterns of responses or extremes in different socio-economic and climate change projections (Figure 4.5c,e). There were also distributions with longer tails and more extreme values, which may significantly increase the probability in certain conditions (Figure 4.5a). In spite of the climatic and socio-economic conditions that might emerge in the region, there was a high probability of substantial drawdown due to groundwater depletion (as suggested by positive normal distribution values) over the area. Also, results showed that due to the uncertain nature of farm income, it was difficult to project the general direction of any future changes. Water demand and soil salinity indices reached peaks around 10% and 20%, respectively, albeit with long tails associated with intensified environmental degradation.

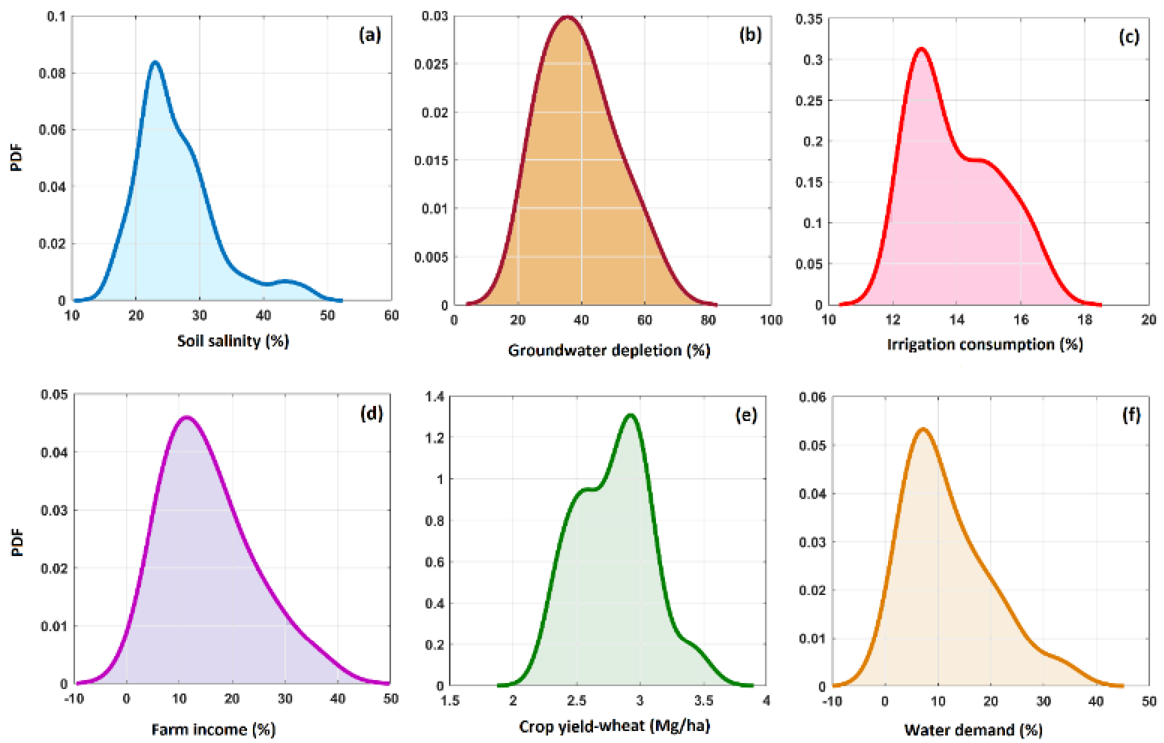

Figure 4.5 The overall uncertainties associated with the integrated model output variables (results for all five storylines at the local level).

Figure 4.6 shows the range of variable values for each of the five storylines. There was overlap between the outcomes of the storylines for each variable. However, the results for most of the scenarios showed distinct peaks, suggesting that a certain range of output values could be safely projected for each scenario. In Figure 4.6, the bimodality and tri-modality seen in Figure 4.5 can also take different forms and as opposed to a combination of scenarios, was a result of separate scenarios, showing a relationship between input variables values and the outcomes. There was a large insensitivity between depletion of groundwater and, to a lesser degree, increased water demand and irrigation consumption for scenarios, which indicated that groundwater conditions and water demands would worsen under the different socio-economic and climate change pressures of all storylines. Soil salinity and irrigation consumption were more sensitive and showed significant variance across different storylines. Groundwater depletion, water demand, and irrigation usage were consistently highest or near-peak in storyline 3. In addition, storylines 2 and 3 showed some of the highest water consumption for irrigation, but the lowest farm incomes. There were notable similarities in storyline 5 for most of the variables, which incorporated both bi- and tri-modal forms due to what was expected to happen in regard to socio-economic and environmental developments (pessimistic/optimistic perspectives) and higher variance of the ISESD model's input values. Furthermore, low values appeared to have a higher degree of confidence and smaller variance. Higher modes with greater variability were likely to have extreme tails of values (e.g., storyline 5 for soil salinity) that were reflected in the plots.

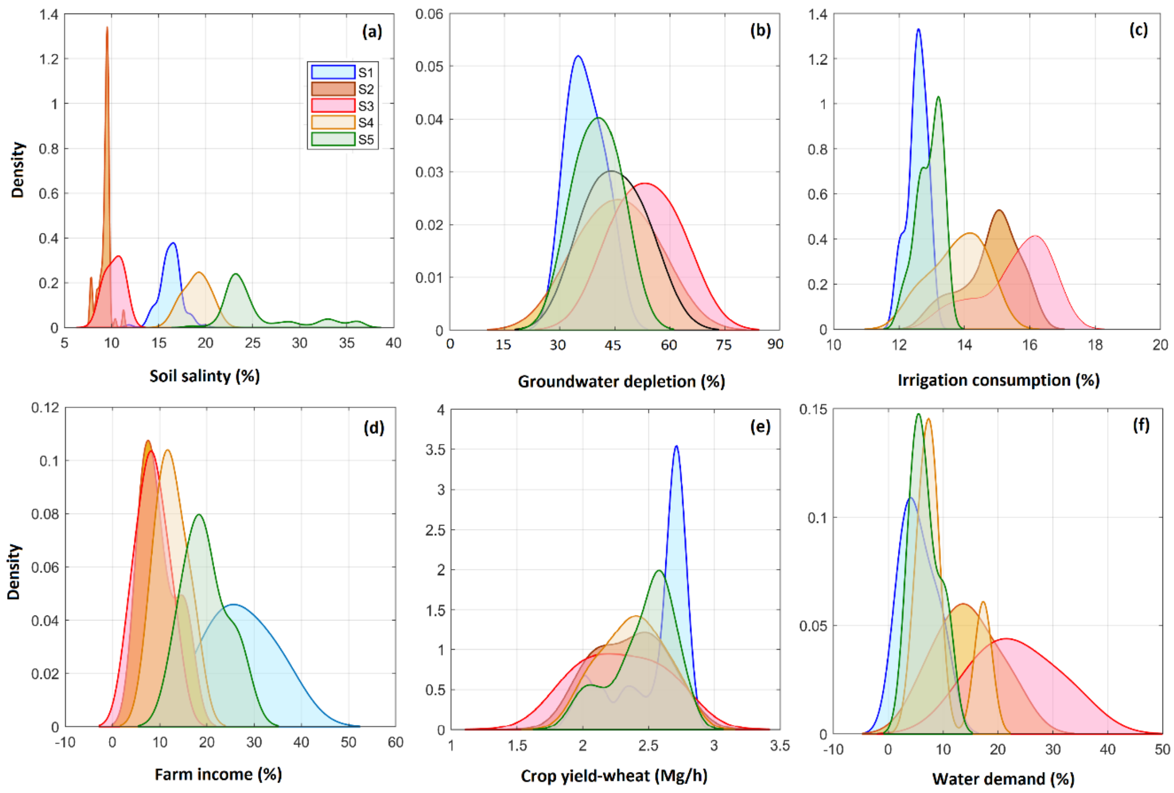

Figure 4.6 Narrative-based uncertainties in the integrated model output variable

4.4.3 Spatial Distribution of the Uncertainties

An average of the storyline variances for each model response from 2020 to 2100 was used to determine the internal variability uncertainty (Deser et al., 2012). Figure 4.7 represents the spatial distribution of the internal variability uncertainty (standard deviation between model runs) across the study area for each of the model's output variables. At the local level, each of the six measures was represented by its associated value and uncertainty. The internal variability uncertainty was developed to identify regions with the highest levels of uncertainty, indicating where the consequences of socio-economic and climate change were likely to be the lowest predictable and model outputs the least reliable. Typically, soil salinity sensitivity was greatest in the eastern portion of the region, while groundwater depletion was more severe in the western part. Moreover, water demands, and crop yields were very variable and uncertain throughout the region. Despite the absence of a discernible pattern, higher values of the metrics were usually associated with greater uncertainty. According to this analysis, even though the magnitude and location of uncertainty varied across the five storylines, they remained similar in general.

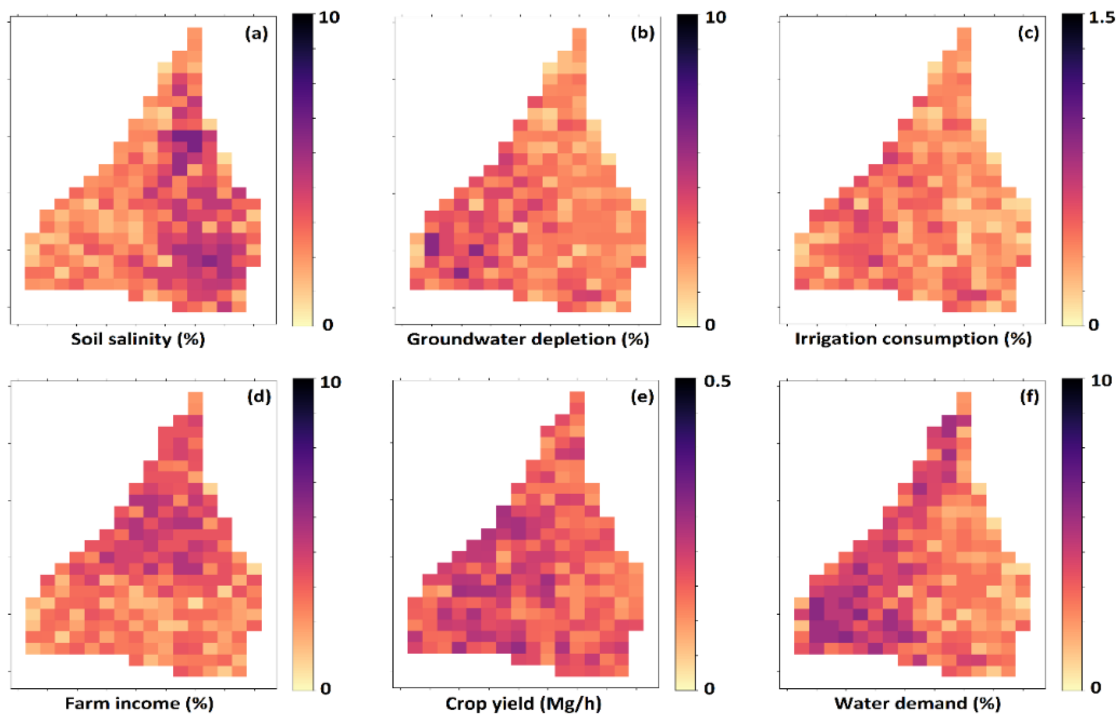

Figure 4.7 Spatial distribution of the internal variability uncertainty across the study area.

With our uncertainty analysis, we investigated whether there was a storyline in which high levels of other socio-environmental outcomes were associated with higher farm incomes in the studied human-water system. We examined whether there was a prevailing narrative that demonstrated a significant relationship between other outcomes and high income. Correlation matrices for all ensembles of scenarios were calculated for this purpose, and the results are displayed in Figure 4.8. Correlation coefficients for the outcomes investigated shed light on the relationship between variables. Although correlation coefficients provide a means for the identification of specific scenarios of interest, they cannot identify individual scenarios of interest. As a result, we conducted a scenario discovery analysis using PRIM for our ensembles' outcomes in order to determine if there existed a prevailing storyline narrative within the ensembles. As an illustration, we examined the relationship between farm income (defined as the percentage change rate from 2020 to 2100) as the outcome of interest, and various socio-environmental factors in the area, including crop yield, irrigation consumption, water demand, soil salinity, and groundwater availability. Figure 4.9 shows the parallel-axis plot relating farm income results to other integrated model outputs in the presence of uncertainty. The findings indicated that there were numerous possible effects associated with high or low farm income. However, this was not a one-dimensional storyline narrative. Under narratives 1 and 5, high farm income values frequently occurred in conjunction with high irrigation consumption and crop yield in the area, implying low environmental standards. The ensemble for storyline 3 demonstrated lower farm income values, which were connected with increased soil salinity and groundwater depletion. While there were some connections between certain outputs, there were also exceptions, demonstrating that numerous distinct scenarios were possible for a given farm income outcome.

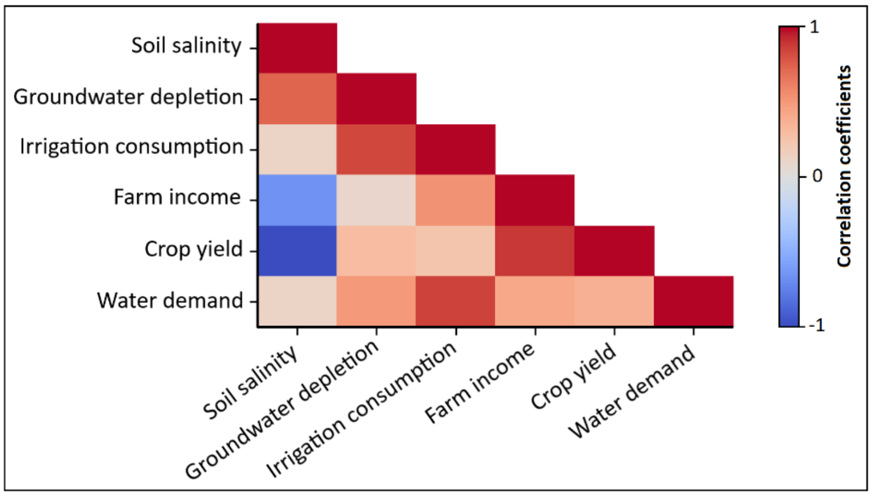

Figure 4.8 Correlation coefficients for the outcomes of integrated model under ensemble of scenarios.

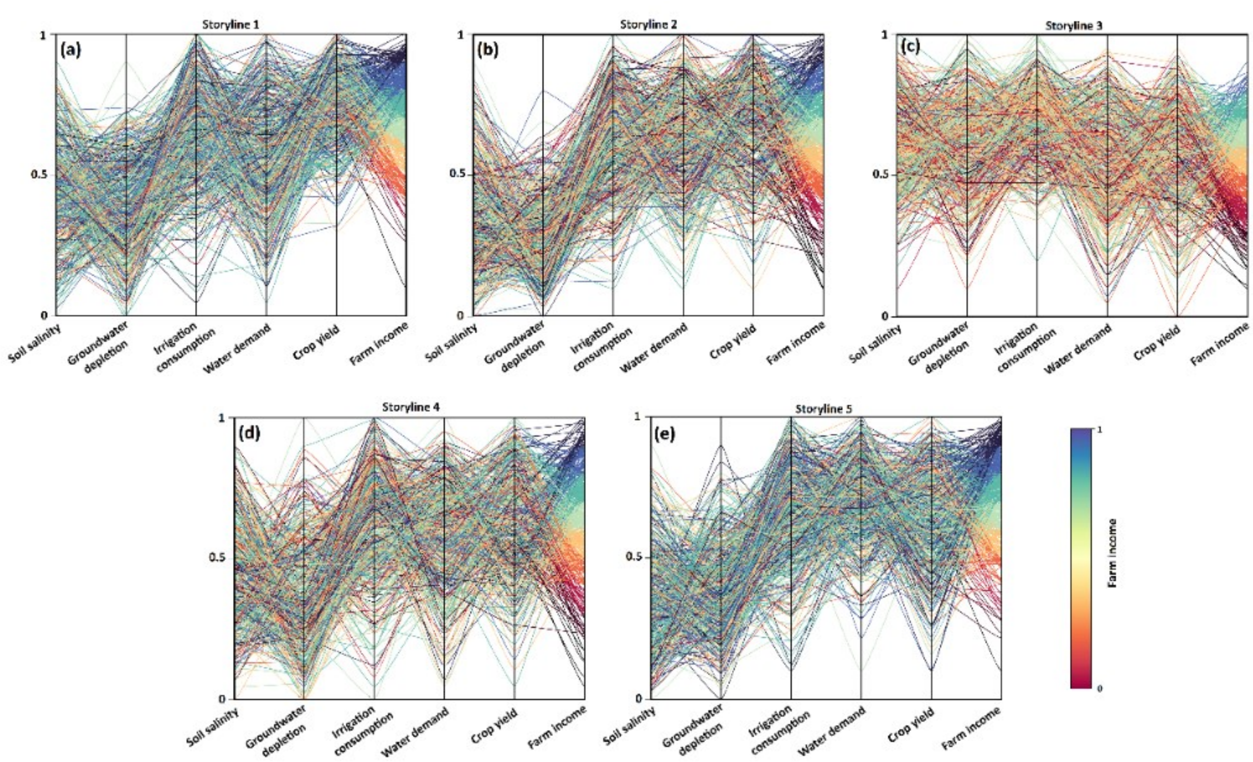

Figure 4.9 Scenario discovery results for different storylines.

4.4.4 Future Projections

During the workshops, stakeholders discussed the effects of possible futures on the human-water system and their consequences. Stakeholders recommended linking quantitative uncertainty with narratives about the most influential local socio-economic and environmental factors affecting policy making, institutional engagement, infrastructure and the economy of the system. In response to stakeholder feedback, the narratives of the storylines were projected for the most critical factors in human-water systems, such as soil salinity and farm income. Consequently, we used the ISESD model to simulate uncertainty associated with stakeholder narratives regarding these critical factors. As an example, in Figure 4.10, the probabilistic envelope for soil salinity increase is shown under the five storylines. In considering the uncertainties for all storylines and probability envelopes of 95, 90, and 85% for soil salinity growth, storylines 4 and 5 (Figure 4.10d,e) resulted in increased soil salinity by 2100, whereas the other scenarios showed less variability. According to storyline 5, soil salinity will increase significantly from 2080 to the end of the century. In all scenarios, the 95th percentile for soil salinity in year 2100 was nearly 60% higher than the baseline level (year 2020).

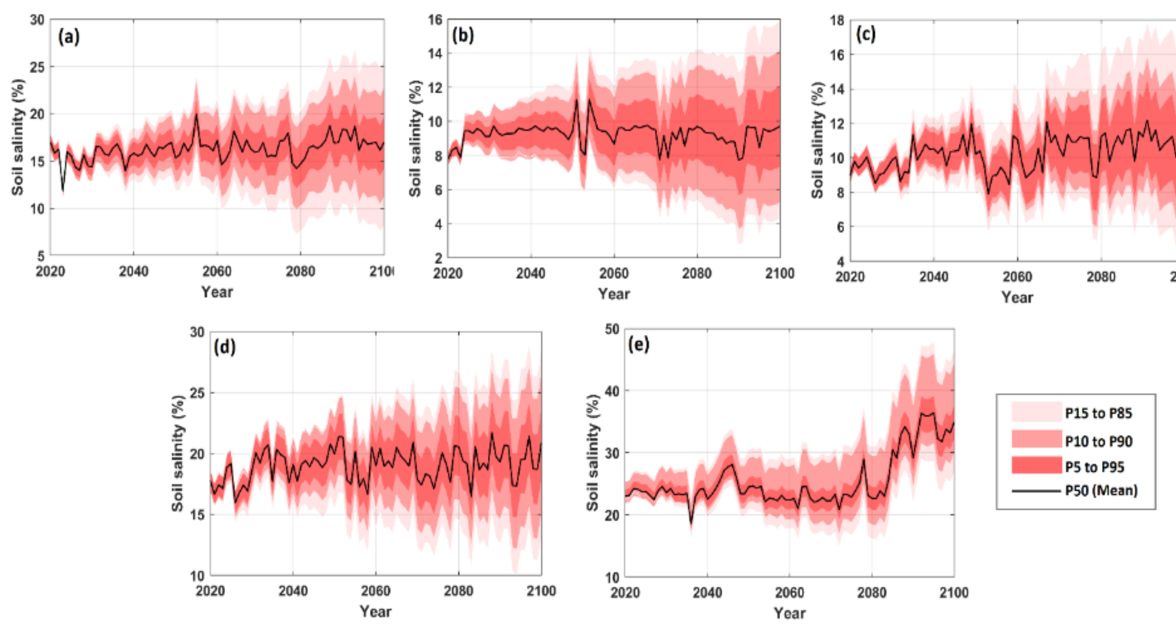

Figure 4.10 The probabilistic envelope for soil salinity increases by 2100 under the five storyline narratives: (a) storyline 1, (b) storyline 2, (c) storyline 3, (d) storyline 4, (e) storyline 5.

4.5 Discussion

Based on derived linguistic values, each variable's storyline generated different PDFs (Figure 4.5). In our case study, most storylines approximated distributions with Gaussian probabilities. These findings confirmed that stakeholders could combine linguistic and epistemic ambiguity with fuzzy sets. For some variables, stakeholders could provide realistic ranges and might replace the expert judgment of impact modellers. Probabilistic distributions were used to describe the fuzzy numbers of the stakeholders in the ISESD model in order to avoid introducing additional assumptions and ambiguous interpretations (Figure 4.3). We also provided stakeholder ranges to allow for a quantitative comparison with impact models' direct quantification of stakeholder-led storylines (Table 4.2). Through our analysis, the proposed framework for converting vagueness to probabilities improved existing strategies of story-and-simulation approaches (Alcamo, 2008), and also increased conceptual and quantitative understanding of uncertainty interpretation and management through storytelling. As a result, we attempted to handle linguistic and epistemic uncertainty by connecting them, since narratives offer holistic perspectives of the future that traditional modelling approaches fail to capture adequately. By merging story-driven information and describing the future, narratives might serve as an additional strategy for enhancing uncertainty awareness (Matthews et al. 2017).

The findings from our impact analyses showed that groundwater depletion was predictable at the local scale, given certain socio-economic assumptions, and might increase if socio-economic and climatic factors change. Groundwater depletion uncertainty was highest in the southern half of the Rechna Doab watershed, particularly in the Lahore and Punjab regions, where agricultural activity and irrigation usage are most uncertain as a result of climate uncertainty and socio-economic factors (Alizadeh et al., 2022; Inam et al., 2017a,b). There was also a correlation between the intensity of increases in water demand and socio-economic instability, which was highest when socio-economic and climate change were rapid and unplanned (storylines 2 and 3; Figure 4.6c), although uncertainty was generally higher and more widespread under those circumstances. Water demand increases did not seem to be related to intensity and were predictable, but there were likely to be some significant changes at the local level. Increased soil salinity was affected by political stability, which was supported by established relationships between fast economic, political and demographic changes and agricultural expansion (Inam et al., 2015). It is likely that crop yield uncertainty originated from the region's sensitivity to precipitation changes, especially under politically unstable conditions (Kirby et al., 2017), and reflected true concerns regarding water availability and usage (Haider and Ullah, 2020). The similarity between some of the storylines suggested any discrepancies that resulted from socio-economic and climatic change were not robust to uncertainties (Kok et al., 2015). This comparison nonetheless produced non-uniform spatial distributions of the specified statistics, which differed (e.g., mean or standard deviation) between scenarios (Figure 4.7), demonstrating that data and storyline uncertainties did not completely eliminate distinctions within scenarios or the relevant relationships between input assumptions and measured outcomes. In regard to the expected character of the outcomes, this predictability exposed a great deal about the expected future implications of socio-economic and climatic change.

We relied on a participatory narrative approach to minimize outliers in the modelling exercises, using perspective methodologies (Offermans, 2016) in the workshops to address uncertainty about stakeholder representation. Our results provided insight into the integrated model's reliability, identified components that might represent substantial sources of uncertainty, and improved our understanding of the dynamic linkages and uncertainties between the systems described by the integrated model (Malard et al., 2017). The selected indicators were characterized by high uncertainties for all storylines, implying the possibility of significant disparities in socio-economic and climate change consequences, adaptation, and vulnerability, especially at regional and local levels. Despite this, we discovered discrete distributions of output values that can be used to estimate limited ranges with a predefined degree of confidence. The bimodal and trimodal distributions also suggested that certain initial conditions might change and result in a more limited range of possible outcomes (Figure 4.6). Moreover, these results have implications for the integrated model's usefulness and reliability, since it appears to be able to logically predict climate change impacts depending on model inputs. According to the integrated model, the most politically and economically unstable scenario (storyline 3) yielded the most unpredictable results, indicating the model could cope with the relatively severe input values that this storyline created without compromising the output reliability.

Furthermore, the findings of our discovery of narrative storylines suggested whether a high farm income is desired, a vast range of outcomes can be achieved. But there is not a straightforward or simple storyline. An advantage of this technique of scenario analysis is that it allows for the discovery of implausible or unexpected uncertainties (Bankes et al., 2013; Kwakkel, 2017). As an example, Figure 4.9 shows an ensemble of scenarios with varying levels of farm income as well as other possible results of the integrated model that may be explored further. We emphasized narrative scenarios 1 and 5 with higher farm income values, which could be useful in determining how farm income can remain high when other environmental metrics such as soil salinity and groundwater depletion are reduced further. There could be more exploration of these possibilities to determine why farm income is low despite numerous factors that indicate the opposite. This framework can be extended to other outcomes of the integrated dynamic model that are of interest, by examining the plausibility of scenarios in relation to the other model's outcomes. Additionally, this form of storyline evaluation may allow for the development of a smaller subset of scenarios that encompass a range of possible futures and desired results.

Although identifying all possible sources of uncertainty, bias, or error can be challenging, it should not prevent the prudent use of techniques such as regional integrated models. Our analysis led to a better understanding and interaction between local communities and modeller-led communities, as well as better integration of qualitative and quantitative techniques by linking disparate concepts of uncertainty (linguistic as well as epistemic and aleatory uncertainties). The findings of this study were solidified by analyzing the quantitative uncertainty of the output of the regional integrated model and enhancing stakeholder input through stakeholder workshops. As a result of the proposed framework, participants acknowledged the value of stakeholders' contributions in characterizing critical aspects of scenarios.

4.6 Conclusion

Integrated modelling methodologies are characterized by inherent uncertainties that are hard to fully represent. Reducing or quantifying these uncertainties is therefore valuable, as their application to an integrated model can help to improve the tool when modelling real-world human-water systems. This study explored an integrated assessment model through the lens of epistemic and linguistic uncertainty analysis of a number of climatic and socio-economic drivers. We investigated how uncertainty in individual drivers impacted the dynamics of socio-economic and environmental change in a real-world human-water system. The research led to a better understanding of the uncertainties associated with input driving factors, output socio-economic and environmental indicators, etc., of the regional integrated assessment model. In the event of simultaneous climate change and socio-economic change, this information is vital for creating a more complete picture of the future impacts at both regional and local levels. Since part of our analysis is an example of uncertainty communication in complex human-water systems, we outlined some reasons that the climate change community should consider narrative approaches more effectively. Using event-oriented rather than probability-based storylines can increase risk awareness because people better understand longer-term events, such as trends, which is more in line with how they perceive and react to risk. As a decision-support tool, narratives may be particularly beneficial for integrating climate change information with other pertinent factors in order to manage compound risk and build suitable stress tests for a particular vulnerability. The use of storylines may act as a physical basis for dividing uncertainty, which permits the use of regional models under certain conditions. In addition, narratives may reach beyond the limitations of standard models to explore the limits of plausibility, thus avoiding false precision and surprise.

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Appendix

4.A.1 Study Area

In this approach, the following steps were used based on method of Pedde et al., (2019):

1. Implementation of stakeholder workshops and documentation of direct outcomes: Facilitators and modelers are subsequently given access to documents that contain all the (relevant) information gathered during stakeholder workshops in order to draft storylines.
2. Drafting storylines: A storyline is developed based on the group's efforts. There is a scenario supporter in each scenario-development group
3. Analysis of workshop narratives and other materials: Each narrative, table, and Fuzzy Set will be evaluated.
4. Distribution of final drafts: A preliminary draft of the model will be available to stakeholders and modelers. Once the second stakeholder workshop is complete, the final draft will be produced.
5. Facilitating interactions between facilitators and modelers.
6. Stakeholder's meeting: Stakeholders' comments on narratives, tables, and results from Fuzzy Sets. Each stakeholder is asked to comment as follows:
   - Are there any changes you wish to make to the content of the narratives?
   - Do you have any comments regarding discrepancies?
7. Next round of stakeholders meeting: The feedback and changes made by stakeholders from Step 6 are implemented. In the second session, narratives, tables, and Fuzzy Set outcomes are presented and discussed in terms of predictions of climate change.

In accordance with the procedure, the following are assured:

- Consistency across storylines is imperative across all variables. The local characteristics should be balanced with logical consistency.
- Stakeholders and modeling team work together in an iterative process.
- Facilitators and modelers must have the ability to capture regional characteristics and interpret workshop results accurately.

4.A.2 Sample Question for the Group Exercise

Question:

What do you think will be the direction and magnitude of the change in irrigation efficiency in 2040, 2060, 2080, and 2100 compared to the baseline year of 2020?

Please describe briefly how Irrigation efficiency changes over time in your scenario using the data in Table S1 and discuss the explanation for this trend.

Table 4.A.1 Linguistic variables and associated trend indicators for quantifying trends in narratives

Linguistic phrase	High decrease	Medium decrease	Low decrease	No change	Low increase	Medium increase	High increase
Trend indicator	- - -	- -	-	0	+	++	+++

Example of explanation:

Please fill in change relative to the baseline year 2020 up to 2100:

A gradual increase in extent up to 2060 owing to the area's low socio - economic status, followed by a quick expansion up to 2100 due to the region's significant improvement in infrastructure and technology.

Table 4.A.2 Example of evolving increase trend for irrigation efficiency up to 2100

Time	2040	2060	2080	2100
Trend change	+	+	++	++

Quantify the vagueness of linguistics:

Please estimate what amounts you mean by "low increase" and "high decrease" in change in the extent of irrigation efficiency compared to the baseline year 2020.

Describe the ranges for each category. Irrigation efficiency is measured as a percentage change per year from 2020.

Table 4.A.3 Example of quantifying linguistics variables

High decrease		Medium decrease		Low decrease		no change		Low increase		Medium increase		High increase	
Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
-	-	-	-	-	-	0	0.1	0.1	0.3	0.4	0.7	0.8	1

4.A.3 Stakeholder Identification

To create our participatory local narratives and ensure that the model accurately reflects watershed dynamics, we identified and categorized the watershed's primary stakeholders and invited them to our workshops. As part of a five-step participatory methodology approach (Inam et al., 2015; Halbe et al., 2018; Perrone et al., 2020), we engaged diverse stakeholders in five processes: (i) problem definition, (ii) stakeholder analysis, (iii) interviewing and developing causal loop diagrams (CLDs), (iv) group CLD development, and (v) simplifying the combined CLD model. On the basis of their desire and technical competency, various stakeholders were asked to participate in the development of local narratives. According to the table below, key stakeholders were identified for the development of local storylines.

Table 4.A.4 Overview of the key stakeholders for the local narrative development process

Category	Stakeholder
Authorities	International Water Logging and Salinity Research Institute (IWASRI) Land Reclamation Department Soil Salinity Research Institute Agriculture Department
Decision Makers	Water and Power Development Authority (WAPDA) Punjab Irrigation Department Ministry of Agriculture and Livestock Local Governments Area Water Boards
Implementers	Agriculture Engineering Department Water Management Department Environmental Protection Agency
Consumers	Local Farmers Domestic Consumers Farmer Organizations

4.A.4 Planning and Preparation for Participatory Workshops

To enhance communication and prepare for the field study, the research team (3 researchers) participated in two workshops with engaged stakeholders (18 stakeholders for workshop 1 and 23 stakeholders for workshop 2). A list of expected roles and responsibilities was provided to stakeholders, and all relevant documents (model descriptions, data, etc.) were available for review and discussion. Workshop planning sessions were held in neutral, third-party venues to minimize distractions and ensure that all workshop attendees were included and available to participate.

Table 4.A.5 Format of the stakeholder's workshop during the local storyline development process

8:30 am – 9:00 am	Greetings and introductions Aims and goals of the workshop Outline and agenda Introduction to the day's activities
9:00 am – 10:30 am	Socio-economic trends and forecasts of main drivers Presentation of sample trends from the model and meaning discussion Assessment of socio-economic impacts Development of plausible scenarios
10:30 am – 11 am	Break
11:00 am – 12:30 pm	Climate change trends and projections Presentation of sample trends from model and narrative discussion Development of plausible narratives Identification of policy choices
12:30 pm – 1:00 pm	Break
1:00 pm – 2:30 pm	Workshop evaluation and closing comments Review, identification, and evaluation of Storylines, strategies, and coping mechanisms Group presentations on local Storylines and narratives Group discussion Comments and suggestions about the workshop Reflections on the day

4.A.5 Design of Key Questions

Stakeholders were given three primary questions on the most influential socio-economic and climate drivers to develop stories and local narrative scenarios:

- How would it be if...? In a scenario of socio-economic and climatic change and development, what kind of local effects are possible? If we don't know for certain how future conditions will be, can we evaluate the implications of various combinations of socio-economic and climate change factors?
- So what…? How important are the outcomes of socio-economic transformation scenarios? The discussion may shift in response to the identified impacts when stakeholders, such as farmers, irrigation distributors, or water resource planners, are presented with them. What long-term effects might socio-economic and environmental change have on the achievement of local development goals?
- Can we do anything about it? Which development priorities should be set for the study area?

How should adaptation be measured?

CONNECTING TEXT TO CHAPTER 5

After evaluating the coupled human-water system of Rechna Doab under different localized SSP-RCPS scenario frameworks developed in Chapter 3, the most uncertain drivers of the system were explored and identified in Chapter 4. Using a quantitative uncertainty quantification method, we tried to explore the plausibility of different uncertainty scenarios by linking qualitative and quantitative methods. The present chapter describes the application of a multi-scenario multi-objective robust optimization framework to extract an optimal robust policy solution for a coupled human-water system, considering deep uncertainty (Chapter 4) for the localized SSP scenarios developed (Chapter 3). A description of the multi-scenario version of multi-objective optimization, robustness, and integrated dynamic model is provided along with the uncertainty analysis.

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The author of the thesis was responsible for the development, testing, and application of the different methods and wrote the manuscript presented here. Prof. Adamowski, the supervisor of this thesis, provided valuable advice on all aspects of the research and contributed to the review and editing of the manuscript. Dr. Manzoor Qadir, Professor at the United Nations University Institute for Water, Environment and Health (UNU-INWEH), helped with the review and editing of the manuscript.

CHAPTER 5: **Multi-Scenario Multi-Objective Analysis of Downscaled Shared Socio-Economic Pathways (SSPs) for Robust Policy Development in Human-Water Systems Under Deep Uncertainty**

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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 global 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 the present study, we propose a new framework that integrates a multi-scenario multi-objective analysis (meta-criteria analysis) of a set of downscaled/localized SSP storylines with the multi-objective robust optimization concept, to find robust optimal solutions under deep uncertainty concerning regional climate adaptation. By developing an integrated dynamic simulation-optimization model, potential policy alternatives are investigated, and their robustness is evaluated based on four key objectives: farm income, groundwater depletion, soil salinity and reliability. 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. As a result, we found Pareto optimal solutions for downscaled SSP scenarios that are both optimally feasible and robustly efficient. Many distinct combinations of outcomes, with varying levels of robustness, were possible under the different SSP scenarios, suggesting that the implementation of a range of potential development processes can lead to a particular outcome of interest. 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. The SSP4 solution represents a compromise between the four objectives, with moderate values for each, while SSP3 was the least desirable of the SSP scenarios examined. Using localized SSPs, the proposed framework demonstrates how implementing robust policy-making with dynamically-integrated modelling of complex human-water systems may provide useful insights for discovering robust optimal policies for regional climate change adaptation.

Keywords: Robust policy making, Multi-scenario multi-objective optimization, Deep uncertainty, Storyline narratives.

5.1 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 analyze 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 analyzed 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 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 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.

The aim of this study is to provide support for policy-making by bridging the literature on multi-scenario multi-objective analysis (meta-criteria analysis) of downscaled/localized SSP scenarios with the literature on multi-objective 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 simulation-optimization 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 multi-scenario, multi-objective decision-making problem evaluates candidate policies. 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. By studying downscaled SSP scenarios in an integrated dynamic model and multi-scenario multi-objective robust optimization model, 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 policies 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.

5.2 Study Area

Situated between the Ravi and Chenab Rivers in central-northeast Pakistan, the Rechna Doab watershed covers 732.5 km2 (Figure 5.1). The Indus Plain has one of the world's major irrigation networks, stretching over 160 × 103 km2 and providing 128 km3 of water annually (Ahmad, 2002; Inam et al., 2017a, b). 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 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 in the 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).

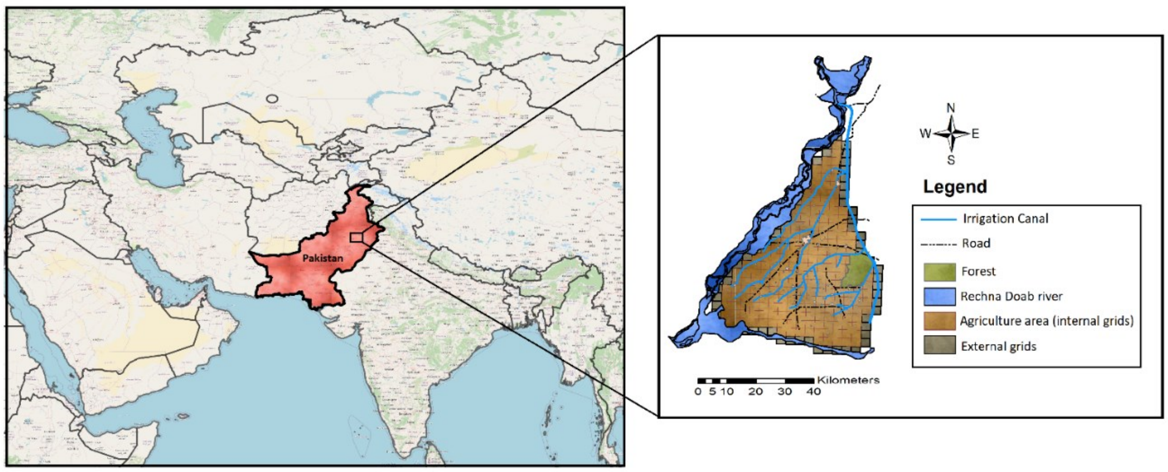

Figure 5. 1 Location of the Rechna Doab watershed within Pakistan (left panel) (base layer credit: OpenStreetMap contributors, 2017) and the human-water system of the Rechna Doab watershed with a grid-based layout of a distributed model map (right panel).

5.3 Methods

5.3.1 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 analyze 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 analyze 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 in a previous phase of the study, 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 5.2 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 multi-objective optimization component during the optimization phase of the multi-objective 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.

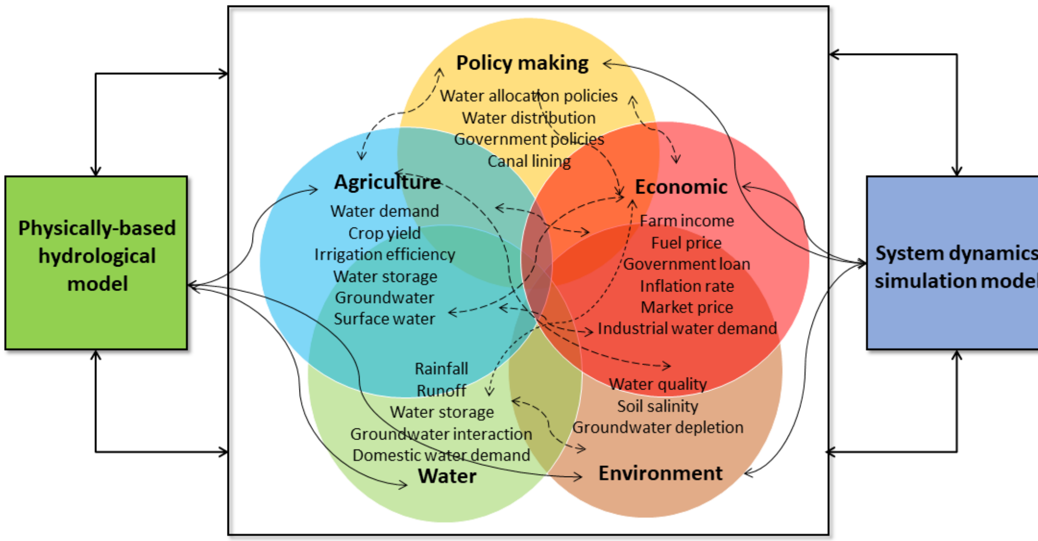

Figure 5.2 Description of the main components of the regional ISESD model, with their key submodules

5.3.2 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 analyzing how SSP variables changed over time, it was possible to elucidate how socio-economic development changed in the 21st 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 analyzing the variables included in the integrated model. Table 5.1 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 environmental drivers in the region. We have chosen the indicators in Table 5.1 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 5.1 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} $(MW·h)^{-1}$	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 5.2 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 5.2 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	
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]

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.

Multi-scenario multi-objective optimization involves multiple conflicting optimization 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 5.3.3.1) with the same meaning, as they must be optimized in the same way.

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

$$\text{Minimize } \{f_{1k}(x), \ldots, f_{ik}(x)\} \quad k \in \emptyset = \{1, \ldots, P\} \tag{5.1}$$

$s.t.\ x \in P \subseteq \mathbb{R}^n$

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

5.3.3.1 Objective Functions

Our proposed framework for adaptation planning, based on SSPs with the multi-scenario multi-objective robust optimization method, 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 multi-objective integrated dynamic simulation-optimization model, the system contained multiple conflicting objectives that had to be balanced in problem solving. The objective functions for the multi-objective optimization model 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.

5.3.3.1.1 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, the 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:

$$f_1(x) = \max\left(\sum_{s=1}^{i} \sum_{p=1}^{j} (R_p^s - E_p^s)\right) \tag{5.2}$$

$$R_p^s = \sum_{i=1}^{I} (P_i \times Y_p^i \times A_p^i) \tag{5.3}$$

$$Y_p^i = f_c\left(Ym_i^p \times \alpha W_i \times \beta S_i\right) \tag{5.4}$$

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.

5.3.3.1.2 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:

$$f_2(x) = \min\left(\sum_{s=1}^{i}\sum_{p=1}^{j} H_{d}{}_p^s\right) \tag{5.5}$$

$$H_d = f_g\left(T^{p,s}, Q^{p,s}, H_0^p, R^{r,s}, k^p, S_y^p\right) \tag{5.6}$$

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 (m3 d^{-1}), H_0 represents the initial depth of the groundwater table (m), R represents recharge to the aquifer system (m3 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.

5.3.3.1.3 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:

$$f_3(x) = min\left(\sum_{s=1}^{i}\sum_{p=1}^{j} EC_p^s\right) \quad (5.7)$$

$$EC_p^s = f_e(EC_0^r, T^{p,s}, Q^{p,s}, H_0^p, R^{r,s}, k^p) \quad (5.8)$$

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.

5.3.3.1.4 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):

$$f_4(x) = min\left(\frac{1}{sp}\sum_{s=1}^{i}\sum_{p=1}^{j}\delta\right) \; where \; \delta = \begin{cases} 1, & (H_d \leq \widehat{H_d} \wedge EC \leq \widehat{EC}) \\ 0, & (H_d \geq \widehat{H_d} \wedge EC \geq \widehat{EC}) \end{cases} \quad (5.9)$$

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.

5.3.3.2 Multi-Scenario Inter-Temporal Open-Loop Solution Strategy

The multi-scenario multi-objective 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):

$$F_t(\overline{x}) = \min\{-f_{1p}(x), f_{2p}(x), f_{3p}(x), -f_{4p}(x)\} \quad p \in \emptyset \tag{5.10}$$

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

5.3.4 Robust Policy Analysis

To explore robust policies, we linked a 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 multi-scenario multi-objective robust optimization method, all created solutions were robust-efficient across all determined scenarios, thereby enhancing robustness and decreasing scenario dependency. Figure 5.3 illustrates the flowchart of the proposed framework for robustness policy analysis in the multi-scenario multi-objective optimization approach. 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 of the optimization problem, problem constraints, etc.

ii) Identify candidate solutions: Using multi-objective evolutionary algorithms (Coello et al., 2007; Reed et al., 2013), candidate solutions are identified by solving a multi-scenario multi-objective optimization problem (Eq. 5.10), 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.

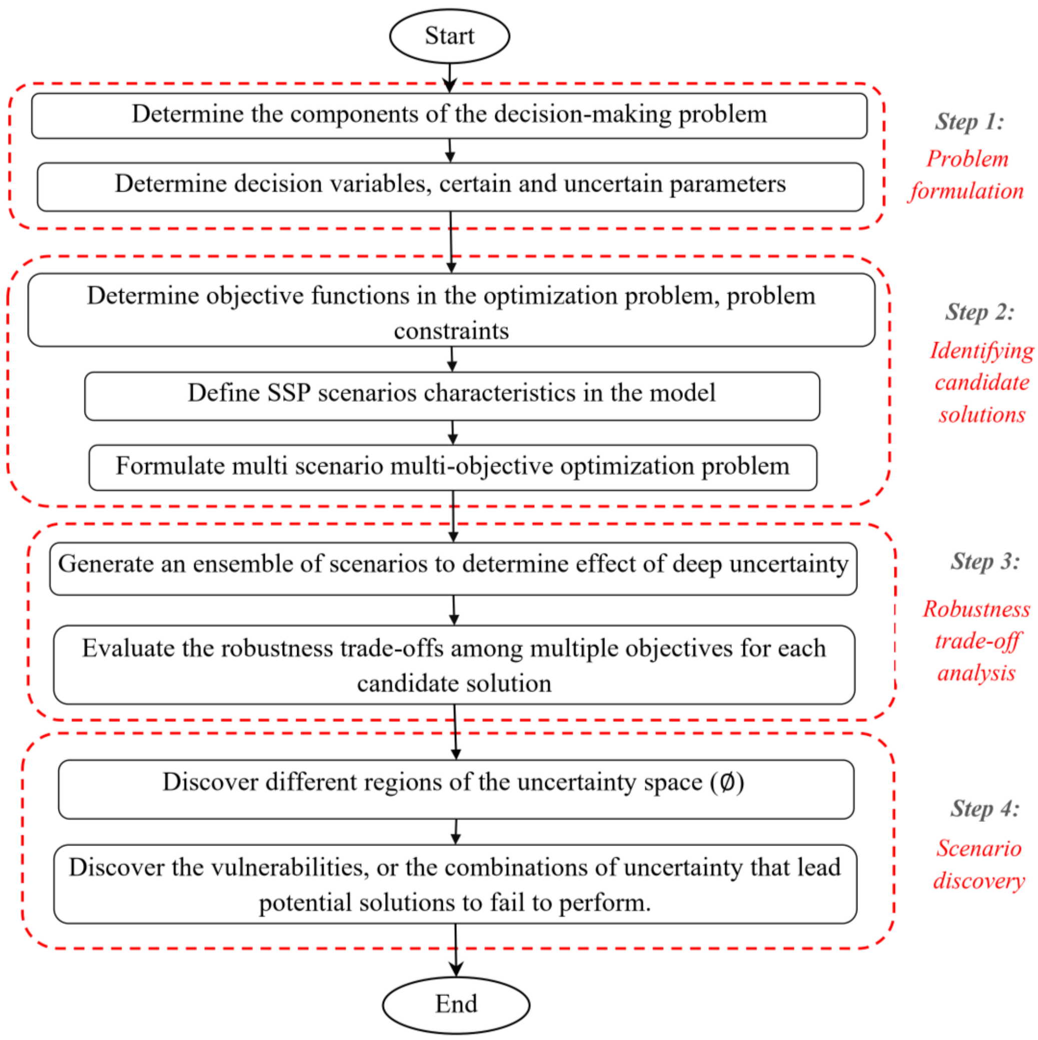

Figure 5.3 Flowchart of the proposed framework for robustness policy analysis in the multi-scenario multi-objective optimization approach

5.3.4.1 Robustness Measurement

To analyze 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):

$$R_{ij} = \begin{cases} \frac{\mu(f_{ijp}^{*})+1}{\sigma(f_{ijp}^{*})+1}, & \Leftrightarrow \ f_i \ to \ be \ maximized, \ \ p = (1, \dots, N) \\ (\mu(f_{ijp}^{*}) + 1) \times \delta(f_{ijp}^{*}) + 1, & \Leftrightarrow \ f_i \ to \ be \ minimized, \ \ p = (1, \dots, N) \end{cases} \quad (5.11)$$

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

5.4 Results

5.4.1 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. 5.2-5.8. Considering the high dimensions of the multi-scenario multi-objective 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 5.4a, 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 5.4b, which connects the trade-offs shown in Figure 5.4a. 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.

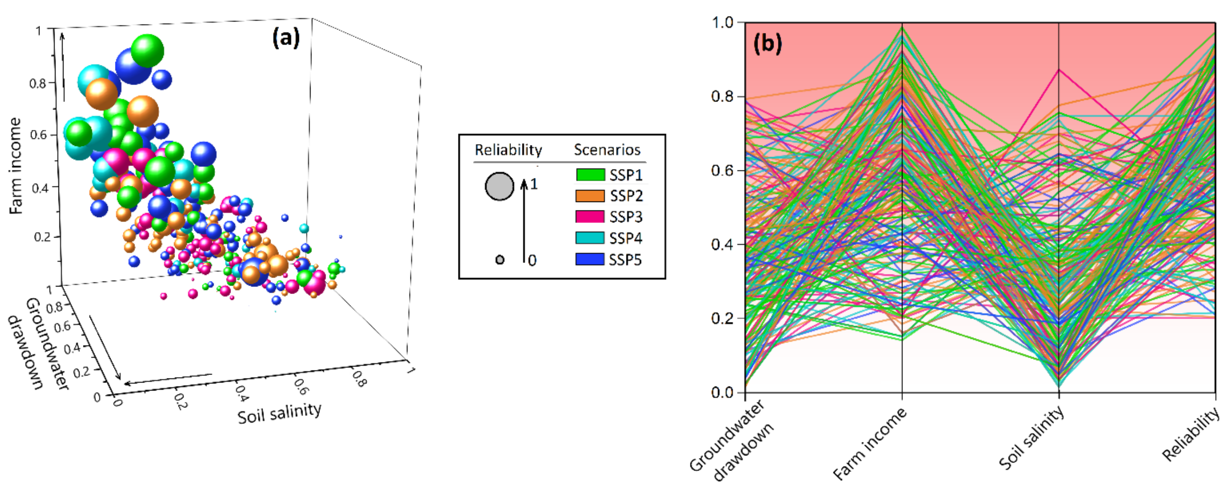

Figure 5.4 The optimal trade-offs under each of the SSP scenarios: (a) Three-dimensional glyph plot demonstrating non-dominant trade-offs and (b) Parallel graph displaying indicators of non-dominated trade-offs and optimum solutions.

Figure 5.5 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 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.

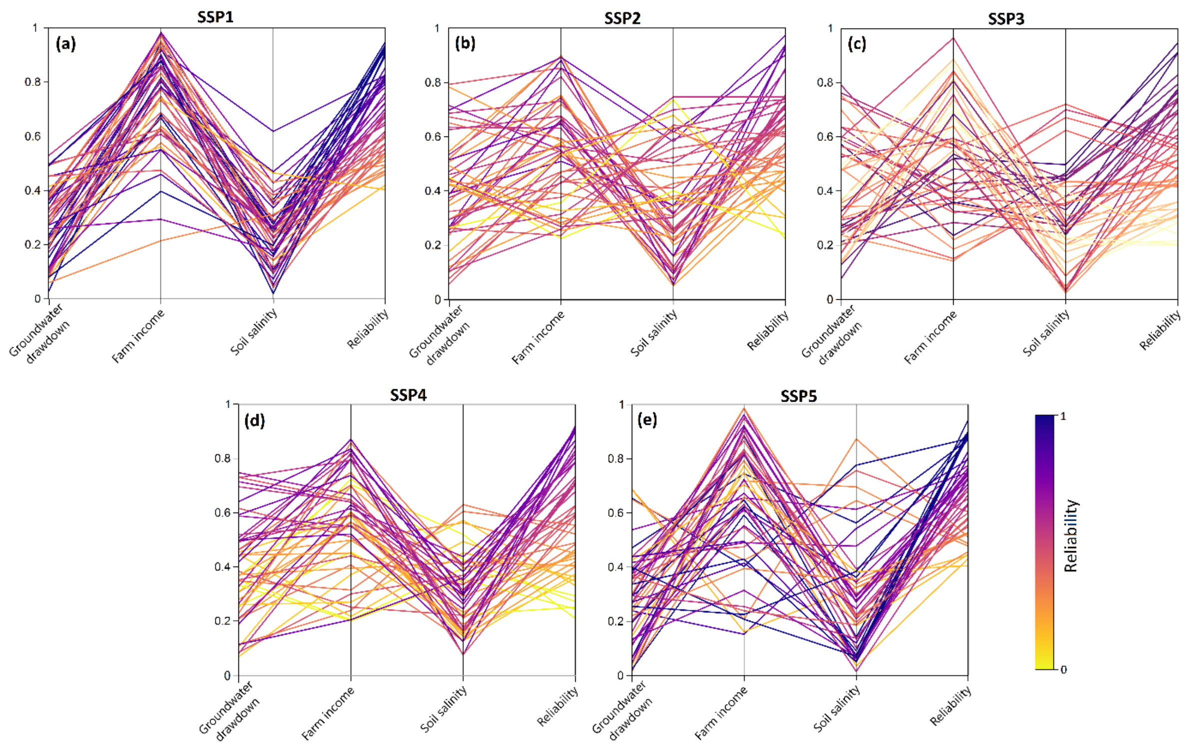

Figure 5.5 Comparing potential solutions to all four objectives in five SSP scenarios.

5.4.2 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 scenarios. Each candidate solution was modelled using 500 experimental scenarios by sampling the seven deep uncertainties indicated in Table 5.2. 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 5.6a illustrates robustness trade-offs among the candidate solutions. Lines indicate the robustness of each potential policy solution, and colours indicate their performance in 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 robustness trade-offs between these four objectives. There are some candidate solutions that exhibit higher favourable robustness values in all SSP situations. As part of Figure 5.6b, a solution is highlighted that illustrates interesting compromises between performance metrics, shown in bold on top of all the transparent solutions.

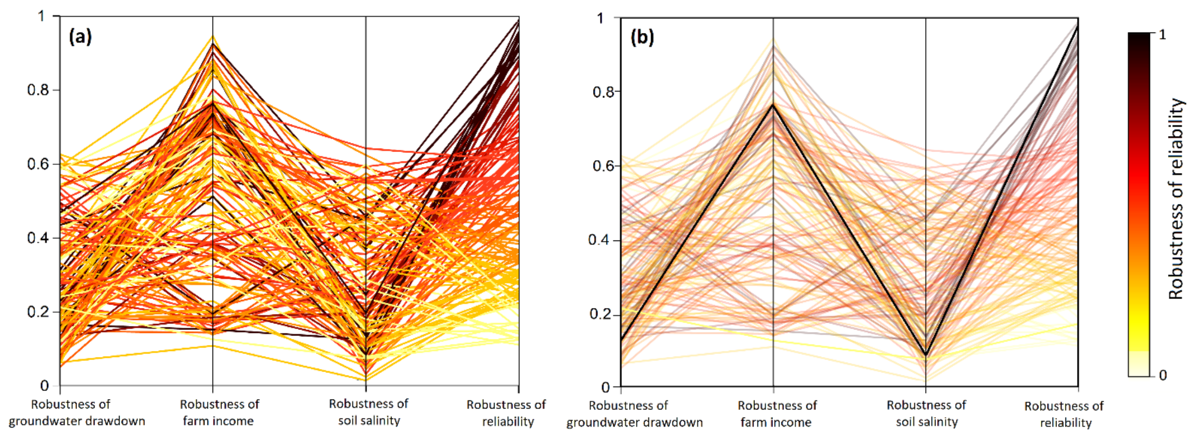

Figure 5.6 Analysis of robustness trade-offs with normalized mean-standard deviation metric

5.4.3 Scenario Discovery

A comprehensive examination of the possible region of vulnerability for each objective over a set of generated computational experiments facilitates the 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 5.7 illustrates the interaction between several deeply uncertain variables (see Table 5.2) 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.

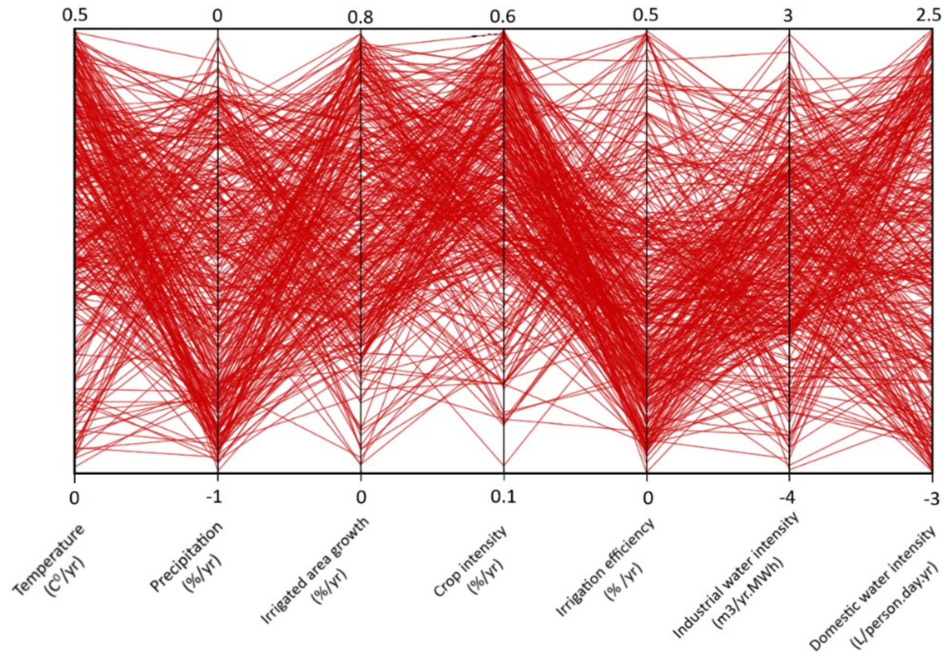

Figure 5.7 Configurations of uncertain variables values lead to reliability failure.

The model-provided division is used along with the scenario discovery technique to determine the final set of candidate scenarios. Figure 5.8 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.

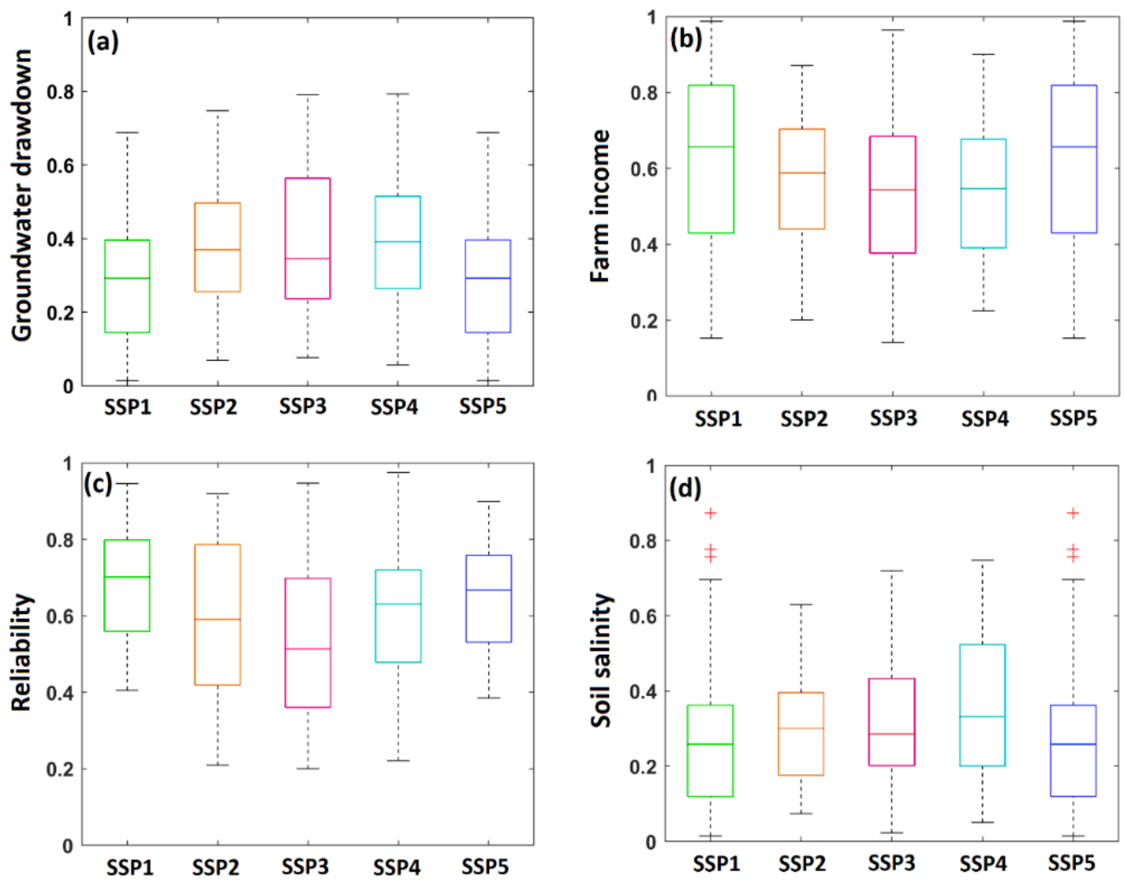

Figure 5.8 Distribution of model's outcomes based on the final discovered scenarios for the five SSPs.

Figure 5.8 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 5.8c). 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 5.8b) and varying levels of reliability (Figure 5.8c) 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.

5.5 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 analyze 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 5.2). 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 5.4). 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 5.5), 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.

The socio-environmental conditions of an SSP scenario have a significant impact on the computed robustness values (Figure 5.6). 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 simulation-optimization 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).

5.6 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 simulation-optimization 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.

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CONNECTING TEXT TO CHAPTER 6

The multi-scenario multi-objective robust optimization framework developed in Chapter 5, suited to exploring optimal robust solutions, provided useful insights regarding the feasible decision variable spaces when considering the inherent deep uncertainty of the system. This chapter presents the steps needed to link the developed framework from Chapter 5 with the concept of resiliency to present a new framework for resilient-robust policy development in coupled human-water systems. This chapter describes in detail the integration of multi-scenario multi-objective robust optimization with a resiliency framework. Use of the integrated dynamic simulation-optimization model for the evaluation of five resiliency metrics is discussed.

This chapter is under review in the journal of *Water Resources Research* (Alizadeh, M.R., Adamowski, J. and Sadegh, M., Mehran, A., 2022. Resilient-robust policy design for coupled human-water systems: Insights form integrated dynamic modeling, Journal of Water Resources Research). The format has been modified to be consistent within this thesis. All literature cited in this chapter is listed at the end of this chapter.

The author of the thesis was responsible for the development, testing, and application of the different methods and wrote the manuscript presented here. Prof. Adamowski, the supervisor of this thesis, provided valuable advice on all aspects of the research and contributed to the review and editing of the manuscript. Dr. Mojtaba Sadegh, Assistant Professor in the Department of Civil Engineering at Boise State University and Dr. Ali Mehran, Assistant Professor in the Institute for Environmental & Spatial Analysis at University of North Georgia provided valuable advice on developing models and helped by reviewing and editing the manuscript.

CHAPTER 6: **Resilience- Based Robust Policy Design for Coupled Human-Water Systems: Insights from Integrated Dynamic Modeling**

Mohammad Reza Alizadeh, Jan Adamowski, Mojtaba Sadegh, Ali Mehran

Abstract

Managing coupled human-water (CHW) systems in an effective manner requires a resilient-robust design, ensuring flexible and implementable adaptation strategies in what are often highly dynamic and uncertain environments. Such management requires a comprehensive understanding and analysis of the feasible space of policy options. Accordingly, a novel resilience-based multi-scenario multi-objective robust optimization framework was developed to identify optimal resilient-robust solutions for a coupled human-water system in response to various future socio-economic and climate forcing scenarios, here represented by a set of downscaled shared socio-economic pathways (SSP) scenarios. We developed an integrated dynamic model to evaluate potential solutions for water extractions and their resilience-robustness in accordance with five resilience objectives under deep uncertainty. Using the Rechna Doab region of Pakistan as a real-world example of a coupled human-water system, we demonstrate how a system's resilience-robustness can vary in response to socio-economic and climate stresses, and how the altered state of ecosystem services affects environmental and economic outcomes. Under various future scenarios groundwater table and farm income proved to be highly sensitive and unstable. While varying spatially across the Rechna Doab region, resilience also showed a non-linear temporal decline. Implementation of our framework highlighted the effectiveness of developing integrated dynamic models and resilience-based multi-scenario multi-objective robust optimization techniques to better describe human-water dynamic interactions and resilience-based policy design. The innovative framework for assessing resilience, developed and applied in this study, will provide stakeholders and model users with a greater understanding of particular variables' vulnerabilities and adaptive capacities in coupled human-water systems.

Keywords: Resiliency, Robustness, Multi-scenario multi-objective optimization, Downscaled SSP scenarios, Deep uncertainty, Integrated modeling

6.1 Introduction

One of the several complex systems contributing to modern societies, human-water systems are vulnerable to a wide variety of threats and risks incurred due to numerous sources of uncertainty and unknowns, i.e., deep uncertainty (Bankes, 2002; Kwakkel et al., 2010; Walker et al., 2012). In planning coupled human-water (CHW) systems' adaptation under deep uncertainty, multiple decision-making approaches have been evaluated; however, the outcomes of these studies have proven to be heavily reliant on the performance measures employed (Maier et al., 2016; Beh et al., 2017; Watson and Kasprzyk, 2017; Borgomeo et al., 2018). Across all scales, these systems can be adversely affected by a wide range of natural and anthropogenic factors (Herman et al., 2020). With deep uncertainty and growing complexity involved in such systems, it is difficult to predict and prevent all potential adverse effects (Walker et al., 2012; Kwakkel et al., 2016). Nevertheless, a variety of frameworks and methodologies that address uncertainty and complexity have been proposed to avoid the worst impacts on coupled human-water systems

Adaptation planning in coupled human-water systems is generally characterized in terms such as optimal performance (Maier et al., 2019), robustness (McPhail et al., 2018), flexibility (DiFrancesco and Tullos, 2014), and reliability (Hyde et al., 2004). These refer to the system's capacity to perform over a wide variety of future conditions and scenarios (Walker et al., 2013; Maier et al., 2016; Quin et al., 2020). Different approaches, representing socio-hydrological complexity from a wide variety of contrasting perspectives, have served in coupled human-water systems planning under deep uncertainty: e.g., Robust Optimization (Ray et al., 2014; Hamarat et al., 2014), Robust Decision Making (Matrosov et al., 2013; Groves et al., 2015; Lempert, 2019), Decision Scaling (Brown et al. 2012; Poff et al., 2016) and Info-Gap decision theory (Roach et al. 2016). Many of these methods evaluate the effectiveness of decisions or strategies by estimating the system's robustness, i.e., how well the system will perform under plausible future conditions. Several alternative approaches designed to identify optimal adaptation solutions for coupled human-water systems have been evaluated: e.g., adaptive dynamic pathways (Haasnoot et al., 2011, 2013; Kwakkel et al., 2015) and multi-objective sequencing approaches (Beh et al., 2015). A changing climate and mounting anthropogenic pressures have led to an increased likelihood of systems degrading and/or collapsing (Mao et al., 2017; Herman et al., 2020; Rad et al., 2022). This has led to questions about how coupled human-water systems react to disturbances and future management uncertainties, making this an ideal opportunity to study the concept of resilience.

In the Anthropocene, when human and water systems must deal with perturbations from each other, the integration of resilience into coupled human-water system modeling is crucial (Mao et al., 217; Falkenmark et al., 2019). Complex links between human and water systems have led coupled human-water systems to experience interconnected paradigm shifts (Rocha et al., 2018). Humans and water systems are likely to be affected in different ways when their resilience changes (Mayer et al., 2014; Carper et al., 2022).

Commonly used in a wide range of fields and circumstances (Fletcher and Sarkar, 2013; Southwick et al., 2014), the term resilience, when applied to a system, describes its ability to absorb disturbances without significantly degrading its performance or form (Walker et al., 2004; Alberti et al., 2011; Konar et al., 2019). A broader definition of resilience is the ability to perform despite constant change and persist in the face of perturbations (Scheffer et al., 2001; Folke et al., 2016). Accordingly, this term refers to a system conceptualized in three dimensions of absorbent, adaptive, and transforming capabilities and permanence for the present, and a reaction to future changes (Xu et al., 2018; Xu et al., 2021). In coupled human-water systems, resilience is the ability of the system to maintain the desired conditions for both human and water components during interactions between the two (Dewulf et al., 2019; Carper et al., 2021). It refers to the system's ability to resist not only socio-environmental threats and climate change, but also internal disturbances arising from human-water interactions (Mao et al., 2017; Xu et al., 2021).

Accordingly, to develop a resilient coupled-human system, it is essential to manage conflicts and trade-offs between stakeholders with conflicting preferences and objectives. These issues can be addressed by resilient robust policy design since they link water resources management and the preservation of the water supply across multiple societal levels, guiding the resource towards a desirable state (Pahl-Wostl, 2015).

To develop more effective strategies for coupled human-water systems, there exists a need for studies and frameworks that offer a more comprehensive synthesis of how optimality and robustness concepts fit with resiliency concepts, particularly where deep uncertainty from multiple plausible futures is concerned. Furthermore, despite numerous studies incorporating resilience criteria in human-water systems, none have applied measurements of resiliency under deep uncertainty tied to a wide range of socio-economic and climate interventions. Moreover, these methodologies' efficacies have yet to be tested in SSP scenario studies. Also, most human-water resilience research relies on conceptual frameworks rather than a quantitative analysis of a real-world case study to discover optimal resilient adaptation policies.

To address these shortcomings, this paper presents a multidisciplinary framework allowing the concepts of robustness and resiliency to be integrated and thereby facilitate the development of adaptation policies in the face of deep uncertainty. The novelty of this study lies in the incorporation of five quantitative resilience metrics in a multi-scenario multi-objective (meta-criteria) analysis, integrated with a robust optimization framework, to assess potential alternatives under a variety of localized SSP (LSSP) scenarios. An integrated dynamic simulation-optimization model was developed to evaluate potential solutions and their resiliency in accordance with resilience objectives. Deep uncertainty analysis was additionally considered when simulating the vulnerabilities of the complex human-water system. The proposed framework served to evaluate the possible resilience and robustness of human-water related vulnerabilities in Pakistan's Rechna Doab region, an example of a multi-stakeholder coupled human-water system under a number of LSSP scenarios. The framework will help adaptation policy-making under future developments and perturbations within LSSP scenarios where there is deep uncertainty surrounding the drivers of future changes.

6.2 Study Area

Located between the Ravi and Chenab rivers, the Rechna Doab watershed in central-northeast Pakistan is an arid and semi-arid region with extensive agricultural activities and irrigation networks that have been profoundly impacted by climate change (Figure 6.1). A changing climate causes highly variable water availability in the area (Ahmad, 2002). There has been excessive groundwater extraction and water logging in this region, which has resulted in a substantial reduction in groundwater levels and quality, resulting in soil and water salinity issues (Inam et al., 2017a; Alizadeh et al., 2022a). The local economy is mainly dependent on agriculture, which in turn significantly affects the environment and the ecosystem. Intensive agricultural practices have resulted in extensive agricultural losses in the region because of soil salinity and groundwater depletion (Inam et al., 2017a, b). In several regions of the basin, land subsidence has transformed the ecosystem (Murtaza et al., 2010). Untreated or improperly treated wastewater discharge has released a variety of pollutants to bodies of water, including metals and metalloids, emerging contaminants, and pathogens (Murtaza et al., 2010). Furthermore, local farmers' agricultural activities are highly susceptible to the effects of climate change on the watershed. With the increasing disruptions and uncertainties, it is imperative to study the resilience of the coupled human-water systems in Rechna Doab.

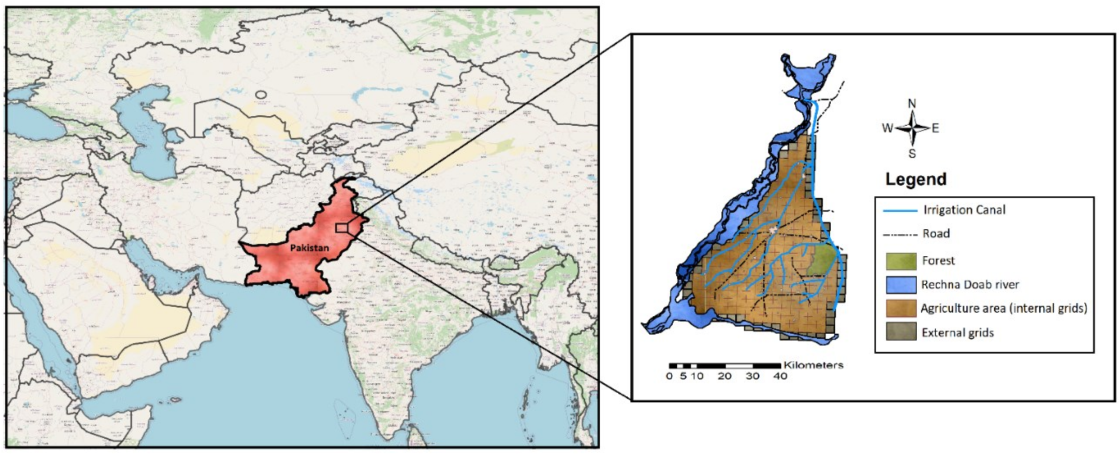

Figure 6.1 Location of the Rechna Doab watershed within Pakistan (left panel) (© OpenStreetMap contributors 2017. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.) and the human-water system of the Rechna Doab watershed with a grid-based layout of a distributed model map (right panel).

6.3 Methods

A set of LSSP scenarios previously developed with local stakeholders (Alizadeh et al., 2022) served to run repeated scenarios simulations. These revealed five localized dynamics narratives and trends to explain how system variables have interacted over time and how they will likely respond to disturbances in the future. In the optimization phase of the framework, the deeply uncertain system variables are determined, and their analysis is evaluated by coupling an integrated dynamic model with a multi-scenario, multi-objective robust optimization model, thereby providing an integrated dynamic simulation-optimization model. Five objective functions based on resilience were explored during the model's optimization search. A resilience assessment (i.e., to what extent certain variables respond to socio-economic and climate disturbances and adaptation conditions under the LSSP scenarios) was then conducted on various system variables, including farm income and groundwater table. The advantage of this method is that it enables locating individual, variable-level failures in a system during a shock or disturbance event. As a result, customized damage mitigation and adaptive capacity measures can be developed more readily. Finally, the robustness of each optimal resilient solution is investigated. The following sections provide details on each of the study's model development stages.

6.3.1 Integrated Analysis of System Resilience

Although some integrated models have been implemented for resiliency and hazard vulnerability assessments, the application of integrated modeling for resiliency analysis is still in its infancy. An integrated dynamic model was developed and applied to evaluate the resilience of the coupled human-water system under a variety of plausible downscaled SSP scenarios based on inputs from stakeholders (LSSP scenarios). An integrated socio-economic and environmental system dynamics (ISESD) model served to analyze socio-economic and climatic effects on local-scale adaptation and mitigation to climate change (Alizadeh et al., 2022a). This model consists of two main components: (i) a system dynamics simulation of the human system (e.g., population, income, awareness, etc.), and (ii) a physically-based simulation of the water system. The developed system dynamics model developed with stakeholders, was coupled with a physically-based (P) hydrological simulator using the Tinamit coupling wrapper (Malard et al., 2017). The model was developed in the earlier phases of this study (Inam et al., 2017a, 2017b; Malard et al., 2017; Alizadeh et al., 2022a) and consists of five core modules: water, economics, agriculture, environment, and policy analysis. By analyzing and identifying possible options based on socio-economics and climate, the model provides quantitative insights. Additional information on the different modules and submodules of the ISESD model can be found in Inam et al. (2017a,b); Malard et al., (2017), and Alizadeh et al., (2022a). Due to its participatory-based development, ISESD's resilience evaluation technique is designed to encourage unrestricted, non-expert stakeholder engagement. Therefore, these approaches are intended to be user-friendly. In addition to preserving stakeholder values and inputs, this method permits enhanced study of complex interactions between multiple system elements and their behavioral dynamics (Inam et al. 2017a; Alizadeh et al., 2022a). Using our novel integrated modeling technique within the domain of resilience, we quantify select resilience features of coupled human-water systems under various socio-economic and climate disturbances of LSSP scenarios. ISESD also focuses directly on system-level resilience using discrete values to quantify system component variable resilience.

To create a fully integrated dynamic simulation-optimization model, the ISESD model is linked with the multi-objective optimization component. We then use this model to evaluate candidate solutions across downscaled SSP scenarios, and examine the resilience and robustness of solution performance for four predefined resilience objectives.

6.3.2 Localized SSP (LSSP) Scenarios Developments for Adaptation and Perturbations of the System

The initial phase of this study involved developing a participatory storytelling method and the development of downscaled SSP scenarios (Alizadeh et al., 2022a). Local storyline narratives depicting various levels of adaptation and mitigation capacity in the system were developed using a scenario development approach (Alcamo & Henrichs, 2008; Rounsevelll & Metzger, 2010). Using global SSPs as boundary conditions, we merged top-down and bottom-up concepts to produce downscaled/localized SSP scenarios. Global SSP attributes were used to construct regional and local SSPs following a top-down approach. In our study, global SSP narratives were mapped onto local storytelling scenarios by applying Zurek and Henrichs' (2007) one-to-one mapping method. An analysis of the local narrative scenarios was carried out by mapping them to global SSPs. The analysis of LSSP factors over time allowed us to determine how socio-economic development and climate change have altered at a local level over the 21st century. We assessed stakeholder perceptions of what might happen through their narratives and what they imagined might happen based on the logic of their storylines for local adaptation planning (Voros, 2003; Alizadeh et al., 2021a). Five narratives were compiled for the coupled human-water system in Rechna Doab, providing an overview of the region's socio-environmental future changes by 2050.

In LSSP scenarios, many forms of system perturbations depending on socio-economic and climate changes (RCPs) are therefore considered. In addition, the systems' adaptation capacities are included and examined in LLSP scenarios based on global SSPs. Consequently, LLSP scenarios indicate various levels of perturbations and adaptability for the local coupled human-water system under consideration. The reader is referred to Alizadeh et al. (2022a) for a thorough discussion of all five developed LSSP scenarios, their main characteristics, trend indicators, etc.

6.3.3 Deep Uncertainty of the System

Several system components can be subject to uncertainty (e.g., decision-making domain, exogenous factors, system outcomes, the importance of outcomes). As a result of deep uncertainty, experts and/or stakeholders do not know the level of uncertainty or disagree about adaptive policies and/or future actions (Pruyt and Coumou, 2012; Tegeltija et al., 2018; Eker and Kwakkel, 2018). Future changes in climatic and socio-economic factors are two significant sources of uncertainty in human water systems. At regional/local levels, we identified several socio-economic and climate factors that significantly contribute to the deep uncertainty of the coupled human-water system under study. Having selected the essential aspects of Rechna Doab, the local characteristics that drive human-water uncertainties in the region were carefully considered. An analysis of the variables contained in the integrated model showed seven deeply uncertain socio-economic and climatic drivers. Based on five downscaled narratives of socio-economic and environmental factors in the region, Table 6.1 presents the deeply uncertain socio-economic and climatic variables and their magnitudes. Based on LSSPs, we suggested potential future change strategies through the selection of indicators in Table 6.1. A comprehensive assessment of these uncertain factors, their extraction, and their origins can be found in Alizadeh et al. (2022b).

Table 6.1 Deep uncertain variable ranges as a consequence of 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	
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]

6.3.4 Multi-Scenario Multi-Objective Optimization Analysis

We developed a multi-scenario-based multi-objective framework that could provide optimal robust and resilient solutions based on downscaled SSP scenarios and incorporated deep uncertainty into the framework (meta-criteria analysis) (Stewart et al., 2013). Identifying solutions that perform well against each criterion is essential when faced with uncertain situations. The purpose of this section is to demonstrate how to implement a framework for identifying the optimal performance under deep uncertainty of $s \in (1, \dots, S)$ LSSP scenarios and for each resilient objectives $r \in (1, \dots, R)$. Performance measurements represent a variety of dimension preferences in the form of resilience objective functions. The resilience objective function (meta-criteria) corresponds to the importance of the criteria based on LSSP scenarios. The optimization process involves many conflicting objectives, and scenarios describe potential future states to represent objectives' uncertainty. The model evaluates performance under all p situations for all m criteria. Meta-criteria analysis was used to investigate the aggregation of decisions (X_0) that provided the optimal performance measure for all $S \times R$ meta-criteria (Miettinen, 2012; Ide and Schöbel, 2016). For each LSSP scenario (S), we analyzed the same number of (R) resilience objective functions in the same manner. Our approach consists of $r = 5$ objectives and $s = 5$ scenarios, with the framework is formulated as follows (Deb et al., 2015)

$$\text{Minimize } \{f_{sr}(x), \dots, f_{sr}(x)\} \quad s \in \theta = \{1, \dots, S\}$$
$$s.t.\ x \in s \subseteq \mathbb{R}^n \tag{6.1}$$

where the scenario space (θ) is defined as a set of possible scenarios (S), and each has m objective functions. The decision variables are $X = (x_0, x_1, \dots, x_{T-1})$, and T is the planning period.

f_{sr}represents the objective function $S = (1, \ldots, 5)$ for LSSP scenario s in the entire scenario space (θ). A multi-scenario multi-objective optimization aims to identify an optimal decision vector X that is feasible under all scenarios S, and that cannot be easily duplicated under a given scenario S with a better value in one objective function m without sacrificing other objectives (Deb et al., 2015; Shavazipour et al., 2021).

6.3.4.1 Resilience Objective Functions

We applied five criteria, each representing a different characteristic of resilience against socio-economic shocks: (*i*) time to baseline-level recovery (Rt), (*ii*) rate of return to baseline (Rr), (*iii*) degree of return to baseline (Rd), (*iv*) total post- disturbance perturbation (Rp), and (*v*) Corrective impact of disturbance (Rci). We selected these five metrics based on their ability to accurately characterize the resilience of two output variables (*e.g.*, farm income and groundwater table depth), in response to transient shocks introduced by socio-economic and climate scenarios. By evaluating variables' capacity to sustain and resist stress, proving how efficiently variables can recover from disturbances, and accounting for the possibility that variables won't be able to regain their pre-disruption functional equilibrium, these approaches allow the identification of possible change scenarios and transformations of variables of interest. Each of the five resilience metrics is illustrated in Fig.2, along with a hypothetical shock-response curve.

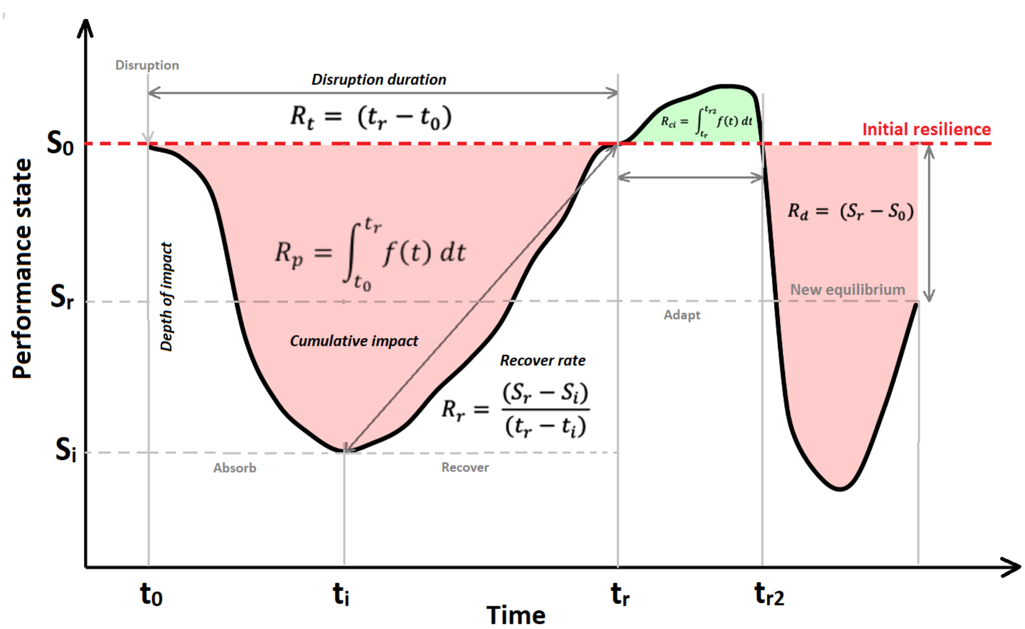

Figure 6.2 Graph of functional response curve with five resilience metrics

6.3.4.1.1 Recovery Function (Rt)

When a disturbance occurs in a system, the recovery time to baseline is the amount of time it takes for the system's attributes to return to their pre-disturbance state. According to Holling (1996), the return time is comparable to the original formulation of engineering resilience. The dynamic response period of the detected function is estimated with this metric. We would expect a relatively fast recovery to the baseline level of functionality if a variable demonstrated resilient behaviour in responding to the perturbation scenario (Figure 6.2). As part of the multi-objective optimization problem, this metric is given as follows:

$$f_1(x) = \min\left(\sum_{s=1}^{i}\sum_{p=1}^{j}(t_r^s - t_0^s)\right) \tag{6.2}$$

where t_0^s represents the time at the start of the experiment (*i.e.*, $t_0 = 0$). It indicates the time at which an event occurs for each variable in each scenario. Following a disruption, t_r^s Indicates how long it takes for the functioning curve to return to normal, *i.e.*, the time required to recover from stress.

6.3.4.1.2 Rate of Return Function (Rr)

The rate of return measures the recovery time as well as the transient reaction impact of the function (Figure 6.2). When a system or factor is resilient, it will return to its normal state faster (at a faster rate or slope) than when it is not resilient. Therefore, the goal of maximizing the rate of return during the planning period is included in the multi-objective optimization problem as follows:

$$f_2(x) = \max\left(\sum_{s=1}^{i}\sum_{p=1}^{j}\frac{S_0^p - S_i^p}{t_r^p - t_i^p}\right) \tag{6.3}$$

where S_i represents the system's operational condition at maximum stress intensity, t_i represents the time when the maximum impact occurs (x-value). S_0 is the system's functioning state prior to the onset of the first perturbations (*i.e.*, $S_0 = 1$).

6.3.4.1.3 Degree of Return Function (Rd)

The degree of return refers to how close the measured function is to return to its predetermined baseline value. The benchmark level is the function's baseline pre-disturbance value or the degree of a theoretical, fully operational system. According to the simulations, the degree of return corresponds to the variation between baseline functionality and the target output after 30 years. Variables that demonstrate resilient sensitivity (as compared to the baseline functional state) return to a level of sustained functionality close to the baseline. Minimizing Rd determines the objective function of the degree of return, as shown below:

$$f_3(x) = min\left(\sum_{s=1}^{i}\sum_{p=1}^{j} S_r^p - S_0^p\right) \tag{6.4}$$

where S_r represents the system's operational state after time horizon simulations. If the desired system state and post-baseline state are the same (*i.e.*, S_0 and $S_r = 1$) at time t = 60 seasons of 30 years of simulations in our case, the functional values at time t = 60 seasons might be comparable to S_0.

6.3.4.1.4 Post-Disturbance Perturbation Function (Rp)

To determine the disturbance effect, the region above the outcome response curve but below the benchmark case was measured. An operational response curve closest to the benchmark border will be narrower for a more resilient system (Fig. 6.2) (Todman et al., 2016; Carper et al., 2021). As defined by the disturbance metric, the most robust reaction would create a function unaffected by perturbation (i.e., perturbation = 0). In the case of variable functionality loss with respect to Rp, the region above the operational reaction output curve was negative, indicating a cumulative loss of function (Figure 6.2). Post-disturbance disturbance is determined by minimizing Rp as follows:

$$f_4(x) = min\left(\sum_{s=1}^{i}\sum_{p=1}^{j} R_p\right) \tag{6.5}$$

$$R_p = \int_{t_0}^{t_r} f(t)\, dt \tag{6.6}$$

Where in an output response curve, $f(t)$, is an area above the benchmark data line but below the output response curve. In the event of a deviation, t_{r2} measures the secondary base recovery time.

6.3.4.1.5 Corrective Impact Function (Rci)

Upon disruption, the corrective impact function metric estimates the possibility of oscillation for a variable when it recovers to baseline. When a variable returns to baseline following a disruption, this metric accounts for overshoot. Any area above the operational response base curve is considered as Rci in the case of a rise in functional behaviour post-disturbance (Figure 6.2; Carper et al., 2021). A high Rci may initially seem to be a positive reaction to a socio-economic and climate disturbance event; however, if it is indicative of more rapid consumption of a limited resource, this may mask a systemic inefficiency. Therefore, the goal of optimizing the corrective impact function during the planning period is included in the multi-objective optimization problem as follows:

$$f_5(x) = max\left(\sum_{s=1}^{i}\sum_{p=1}^{j} R_{ci}\right) \tag{6.7}$$

$$R_{ci} = \int_{t_r}^{t_{r2}} f(t)\, dt \tag{6.8}$$

Where t_{r2} is the secondary baseline recovery time in the event of a fluctuation.

6.3.4.2 Strategy to Solve a Multi-Scenario Multi-Objective Framework

In this study, an open-loop intertemporal solution method (Ward et al., 2015; Hadka et al., 2015; Eker and Kwakkel, 2018) in multi-scenario form was used to solve the multi-scenario, multi-objective optimization problem. The formulation for the suggested problem's optimization solver is as follows (Deb et al., 2015):

$$F_t(\overline{x}) = \min\{-f_{1p}(x), f_{2p}(x), f_{3p}(x), f_{4p}(x), f_{5p}(x)\} \;\; p \in \emptyset \tag{6.9}$$

6.3.5 Trade-Off Simulations and Robustness Analysis Procedure

To investigate resilience of policies, we coupled a multi-scenario multi-objective robust optimization framework with our integrated system dynamic model (ISESD) to investigate multiple objectives in distinct LSSP situations. During this method's search process, all developed solutions will be resilient across all defined scenarios, which will increase robustness and decrease scenario dependence. We created an iterative process that includes multiple decision analysis approaches on a multi-scenario form of robust multi-objective decision making (Kasprzyk et al., 2013; Eker and Kwakkel, 2018; Shavazipour et al., 2021) as follows:

i) Problem identification phase: Characterization of problem features, including decisions, resilience indicators, deeply uncertain factors, complex interrelationships, performance indicators, optimization objective functions, problem constraints, etc.

ii) Determine optimum solution: Use of multi-objective evolutionary algorithms (Deb, 2015; Reed et al., 2013) to solve multi-scenario multi-objective optimization problems (Eq. 6.10).

iii) Deep uncertainty and robustness analysis: Assessing the trade-offs between numerous resilience objectives for each potential solution across LSSP situations using an ensemble of scenarios developed to study the effects of deep uncertainty. Afterward, alternatives are re-evaluated in light of a broader range of possible scenarios to determine their robustness and uncertainty impact.

6.3.5.1 Robustness Measurement

To evaluate the robustness of trade-offs among objectives, the mean-standard deviation is used (Hamarat et al., 2014; Kwakkel et al., 2016). The idea of achieving an accurate mean with the smallest possible deviation is integral to using index mean-standard deviation. According to the signal-to-noise ratio of control theory, this mean/standard deviation can be expressed mathematically as (Eker and Kwakkel, 2018):

$$R_{ij} = \begin{cases} \frac{\mu\left(f_{ijp}^{*}\right)+1}{\sigma\left(f_{ijp}^{*}\right)+1}, & \Leftrightarrow\ f_i \ to\ be\ maximized,\ \ p = (1, \ldots, N) \\ \left(\mu\left(f_{ijp}^{*}\right)+1\right) \times \delta\left(f_{ijp}^{*}\right)+1, & \Leftrightarrow\ f_i \ to\ be\ minimized,\ \ p = (1, \ldots, N) \end{cases} \tag{6.10}$$

where $\mu\left(f_{ijp}^{*}\right)$ is the mean of the result scenarios for the indicator f_i, and $\left(f_{ijp}^{*}\right)$ represents the standard deviation, when candidate solution j is removed.

6.4 Results

6.4.1 Resilience Metrics Analysis

Analyzing resilience metrics involves evaluating how each suggested measure performs in expressing system resilience in the face of a variety of socio-environmental and climatic pressures. The resilience features measures for each adaptation strategy were determined based on the LSSP scenarios for each future socio-environmental projection, resulting in unique findings for each performance metric. In Figs. 3 and 4, half violin plots are used to illustrate the distribution and probability density of data points for each resilience metric. The system's resiliency is determined by the sensitivity of each indicator under varying levels of system adaptability across the LSSP scenarios.

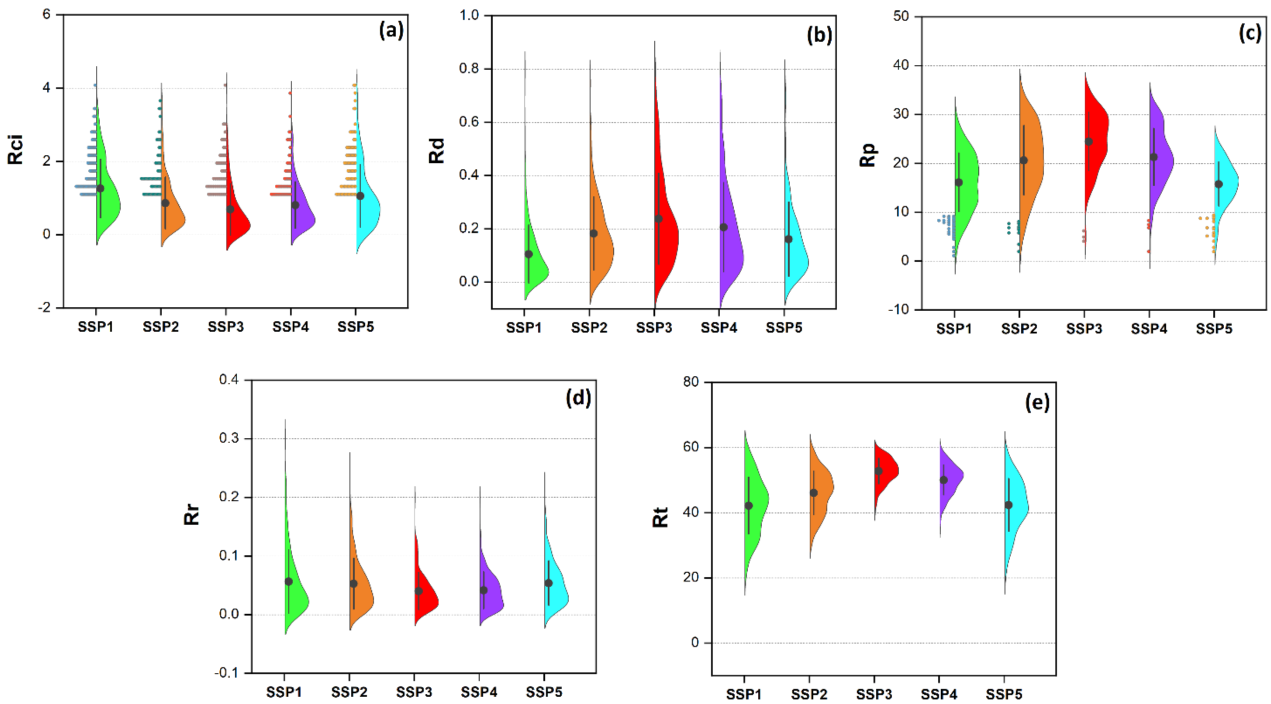

Figure 6.3 Distribution of the resilience performance metrics for groundwater table depth across all LSSP scenarios and adaptation options

Median values of most metrics start improving as the level of adaptive capacity inherent to LLSPs grows (Figure 6.3). However, certain metrics (*e.g.*, Rp, Rt, and Rci), exhibit better performance under SSP1 and SSP5 than under other scenarios. Under SSP1 and SSP5, an increase in system adaptation reduces the time it takes for the system to return to baseline, the degree of return to baseline, and the overall degree of post-disturbance perturbation. Greater mitigation and adaptation challenges, unsustainable policies, high resource demands, and slow technological advances result in SSP3 portfolios performing poorly across most resiliency metrics. Delayed technological improvements under SSP3 result is a high demand for local water resources, resulting in worsening groundwater depletion (Figure 6.3) and farm income (Figure 6.4). This, in turn creates greater mitigation and adaptation challenges and reduces the capacity for resilience.

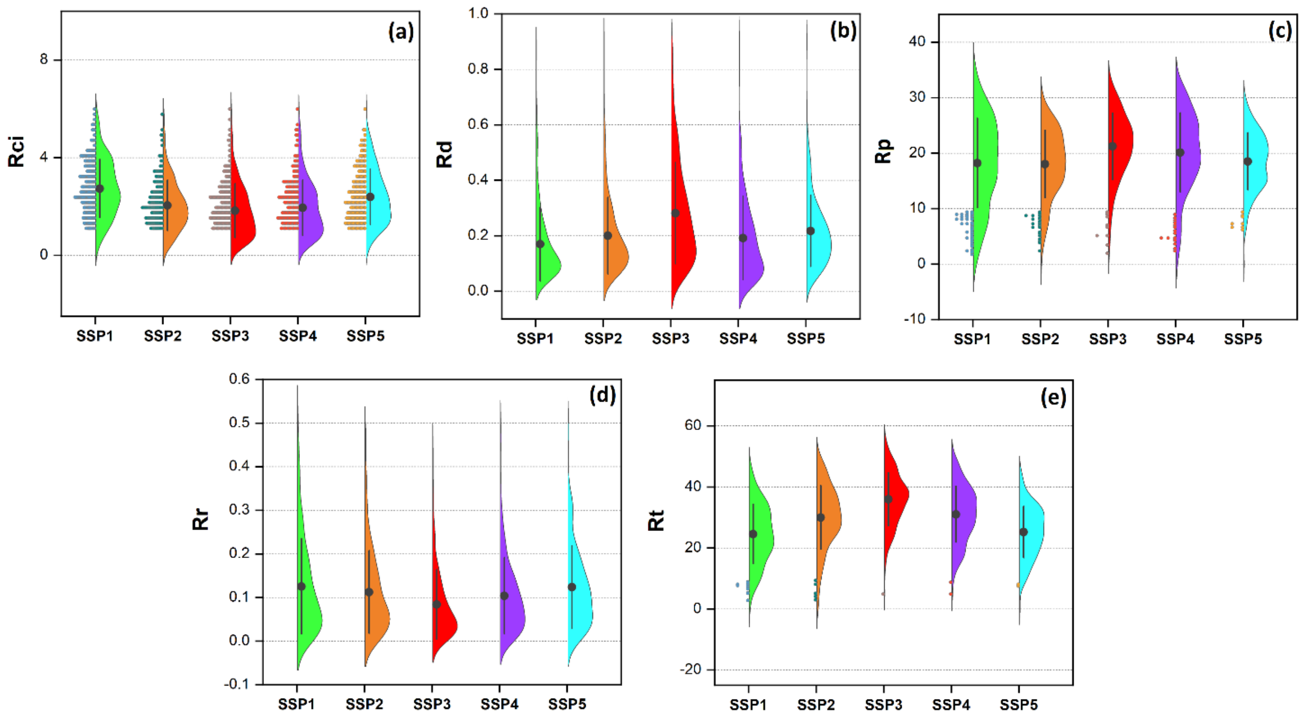

Figure 6.4 Distribution of resilience performance metrics for farm income across all LSSP scenarios and adaptation options

To better understand the distinctions between the five LSSP scenarios, we analyzed the patterns of the system's resiliency indicators. The plots in Figures 6.5 and 6.6 show parallel coordinates for the groundwater table and farm income, respectively, providing a comparison of the impact of LSSP scenario adaptations and mitigations on decision-making policies for system resiliency based upon multi-scenario multi-objective optimization. In these figures, colored lines represent normalized metrics for different scenarios and optimal solutions of water extractions. For various scenarios, the value for return time to baseline level recovery is represented by colored for the extraction portfolio of water resources.

Figure 6.5 illustrates the performance of Pareto optimal solutions based on five resiliency indicators for groundwater table in five LSSP scenarios. Solutions are color-coded according to their return time to baseline recovery performance. Green with a darker hue indicates greater recovery ability. In most LSSP situations, groundwater depletion and decreasing farm income were associated with a decline in resiliency indicators. Furthermore, several scenarios involve substantial trade-offs between objectives, especially SSP5 and SSP1. Compared to other solutions, SSP1 and SSP5 tend to show greater groundwater and farm income stability, suggesting that during the implementation of these LSSPs, eco-friendly policies and practices (such as protecting natural resources) might cause less harm to the environment (*i.e.*, less soil salinity or groundwater depletion). Dark red lines in the graph, which denote significantly diminished resilient performances in the SSP3 scenario, indicate solutions that result in severe environmental degradation.

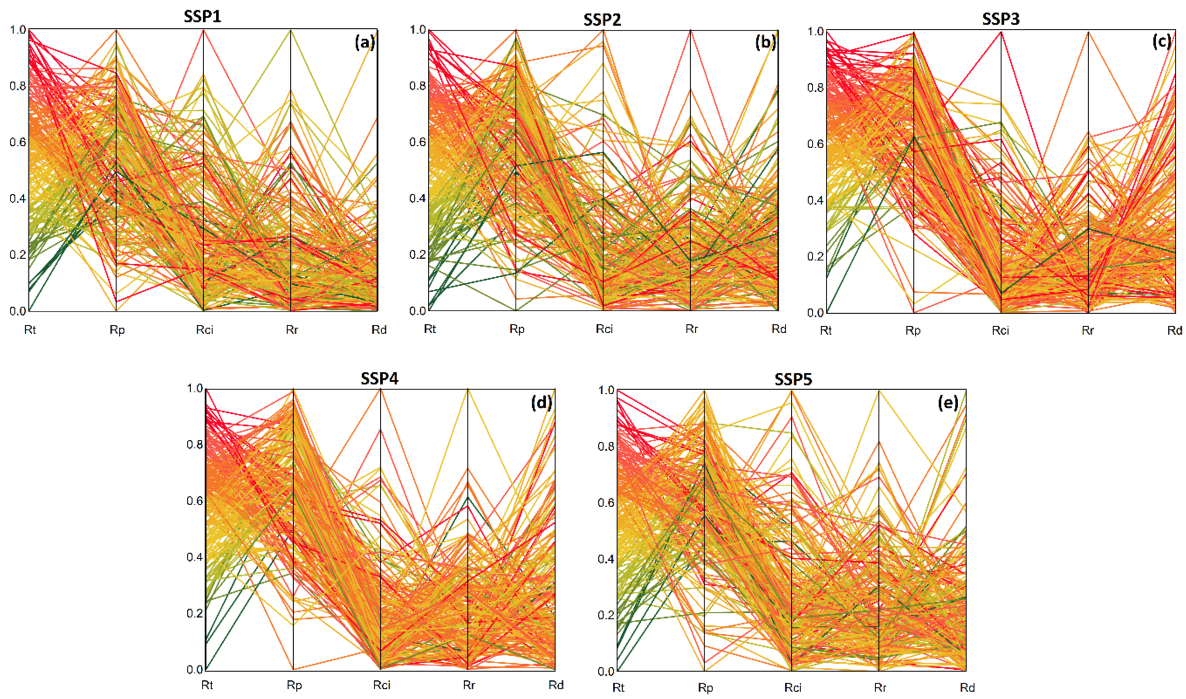

Figure 6.5 The performance of Pareto optimal solutions based on five resiliency indicators for groundwater table depth in five LSSP scenarios

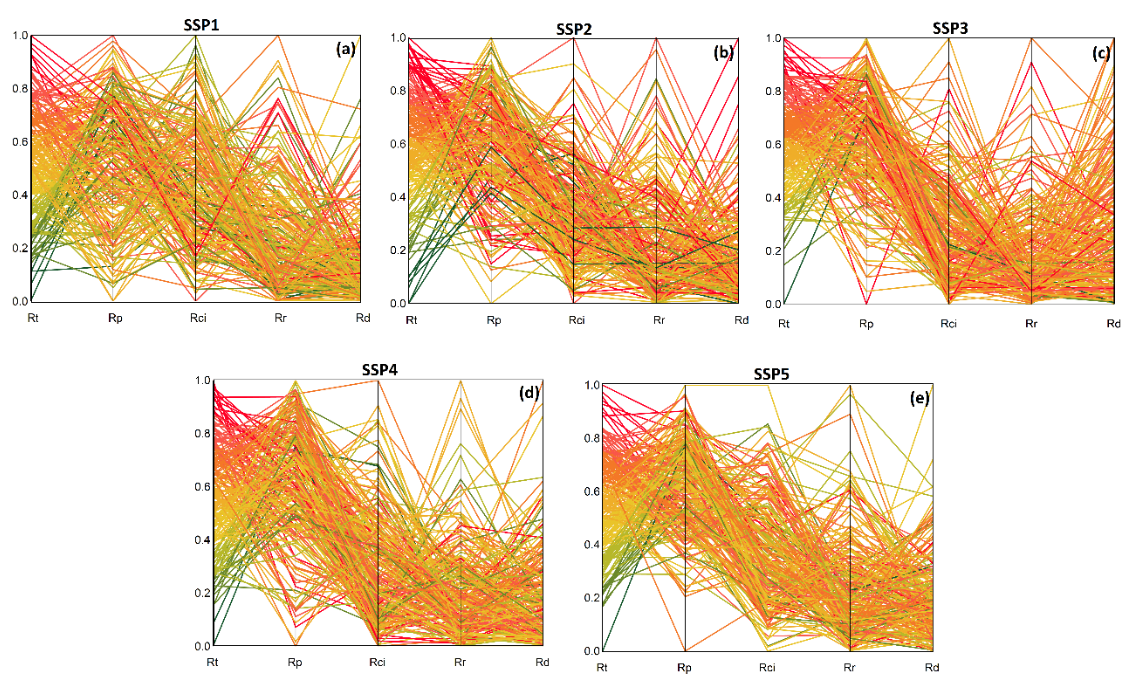

Figure 6.6 The performance of Pareto optimal solutions based on five resiliency indicators for farm income in five LSSP scenarios

6.4.2 Robustness Analysis of Resilient Solutions

Considering the deep uncertainties associated with LSSPs' socio-environmental conditions, the robustness of the candidate resilient solutions generated by the LSSP scenarios were assessed through an examination of a variety of scenarios as part of the analysis of each potential solution. To re-evaluate and examine the optimal solutions obtained by the integrated dynamic simulation-optimization model, a total of 500 experimental scenarios were constructed using Latin Hypercube Sampling. A sampling of the seven deep uncertainties (Table 6.1) generated 500 experimental scenarios for each candidate solution. Afterward, a robustness evaluation of the potential solutions based on five LSSP scenarios was performed. For the 500 generated experimental scenarios, mean-standard deviation measurements were carried out to determine the robustness of the solutions. Based on this measure, Figure 6.7 depicts the distributions of robustness density for all candidate solutions. Candidate solutions resulted in a wide variety of trade-offs between robustness and performance in all LSSP scenarios. In scenarios with improved adaptation and mitigation capabilities, such as SSP1 and SSP5, the normalized mean, and standard deviation provides a larger value for robustness.

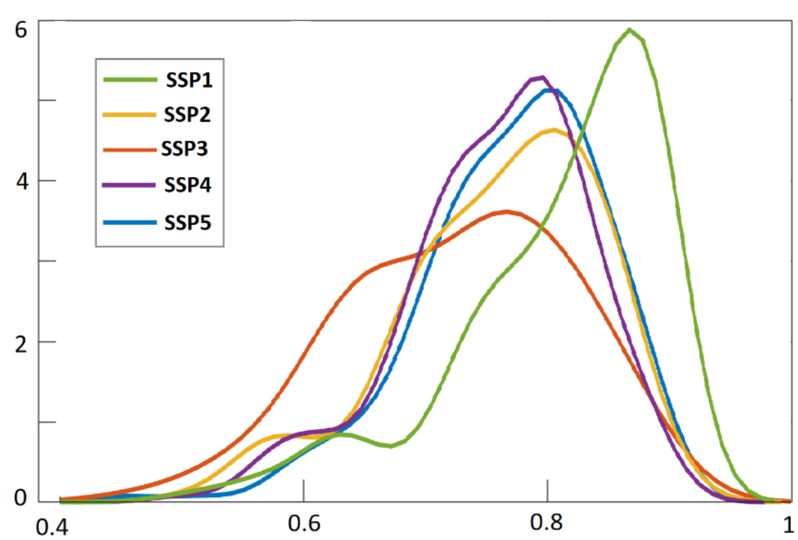

Figure 6.7 The robustness density distributions of the solution space derived from the means-standard deviation metric

6.4.3 Systems' Transient Resilience Characteristics

Figures 6.8 and 6.9 depict the transient behavior of groundwater table depth and farm income variables, respectively, in five different LSSP scenarios over a 30-year planning horizon (2020–2050). Based on each LSSP scenario, the time series illustrate the behavioral patterns of groundwater tables (Figure 6.8a) and farm incomes (Figure 6.9a). The bar graphs in the figures (panels b-f) provide a quantitative analysis of resilience metric values for the coupled human-water system in Rechna

Doab.

Figure 6.8 shows that groundwater table disturbance levels and return durations were large even under the least severe socio-environmental shocks. Moreover, Rci values were substantially lower for groundwater-table depth, indicating a very poor performance overall. As the duration of LSSP disturbances were extended, all five indicators of groundwater-table depth worsened. Most resiliency metrics, including Rci, Rt, and Rp values, showed that the adaptability of systems under different LSSP scenarios differed in their impact on groundwater table depths.

For the SSP3 adaptation scenario, farm income showed a pattern of high degrees of return to baseline (Rd) values and extremely high return times to baseline-level recovery (Rt) (Figure 6.9). Based on resilience values for Rt and Rd, farm income performed the worst under SSP3 socio-economic conditions.

Under the SSP1 scenario, groundwater and farm income conditions showed the best results as their resilience measures closely matched ideal resilience values. Both groundwater table and farm income began exhibiting vulnerabilities under greater intensities of increases in water demand and socio-economic instability. This occurred when socio-economic and climate change was rapid and unplanned, as in SSP2 and SSP3. As a result of disturbed conditions under SSP3 and SSP4, two variables displayed extremely high Rp values (Figures 6.7b and 6.8b), demonstrating that they all significantly deviated from their baseline functional patterns. In this case, Rt was also very high, indicating that the variables did not return to their initial condition. After socio-economic and climatic disturbances were applied under LSSP pathways, the groundwater table and farm income variables were incapable of returning to baseline, *i.e.*, the groundwater table cannot recover from perturbations of that magnitude and duration. These results indicate that these variables are highly sensitive and unstable in shock scenarios of this type.

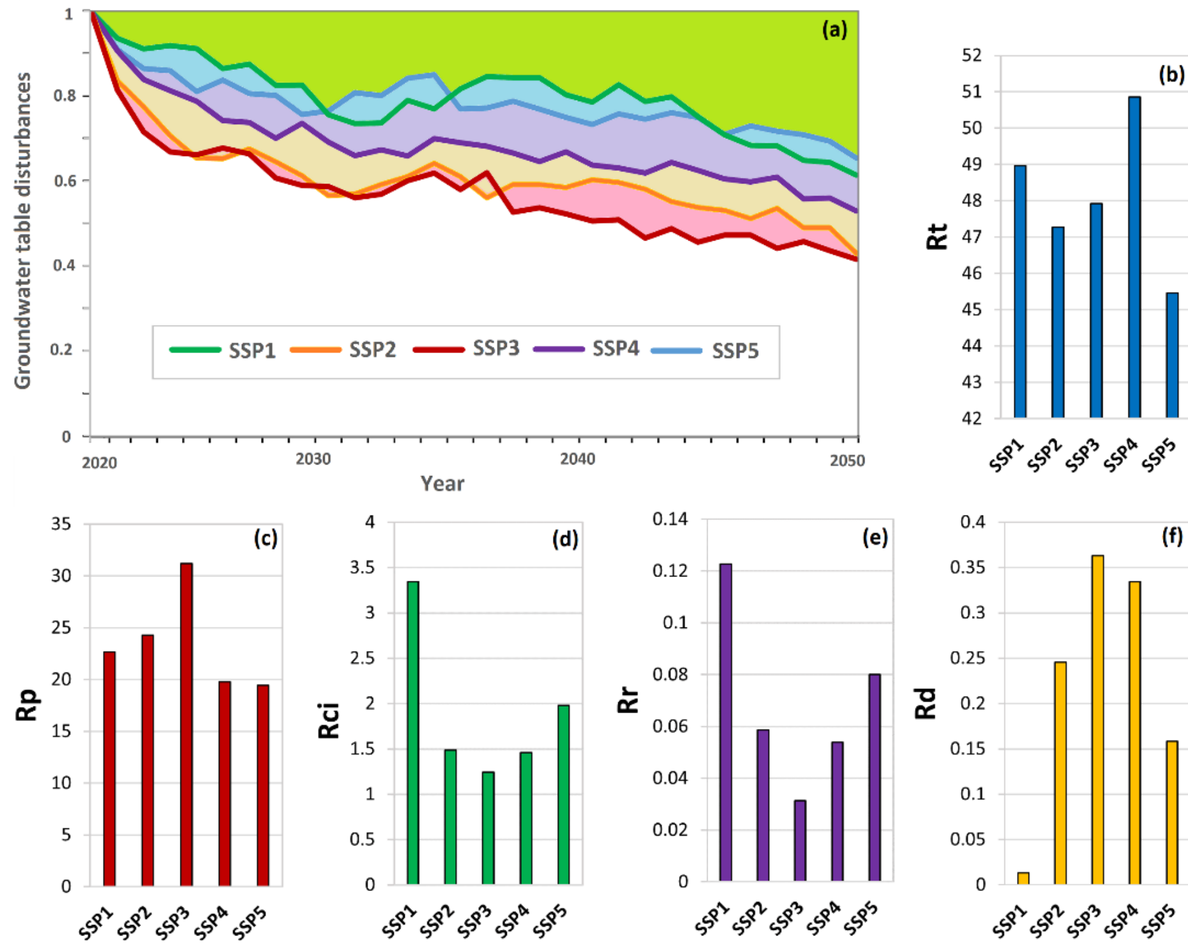

Figure 6.8 The transient behavior of groundwater table depth and corresponding resiliency metric values under various LSSP scenarios

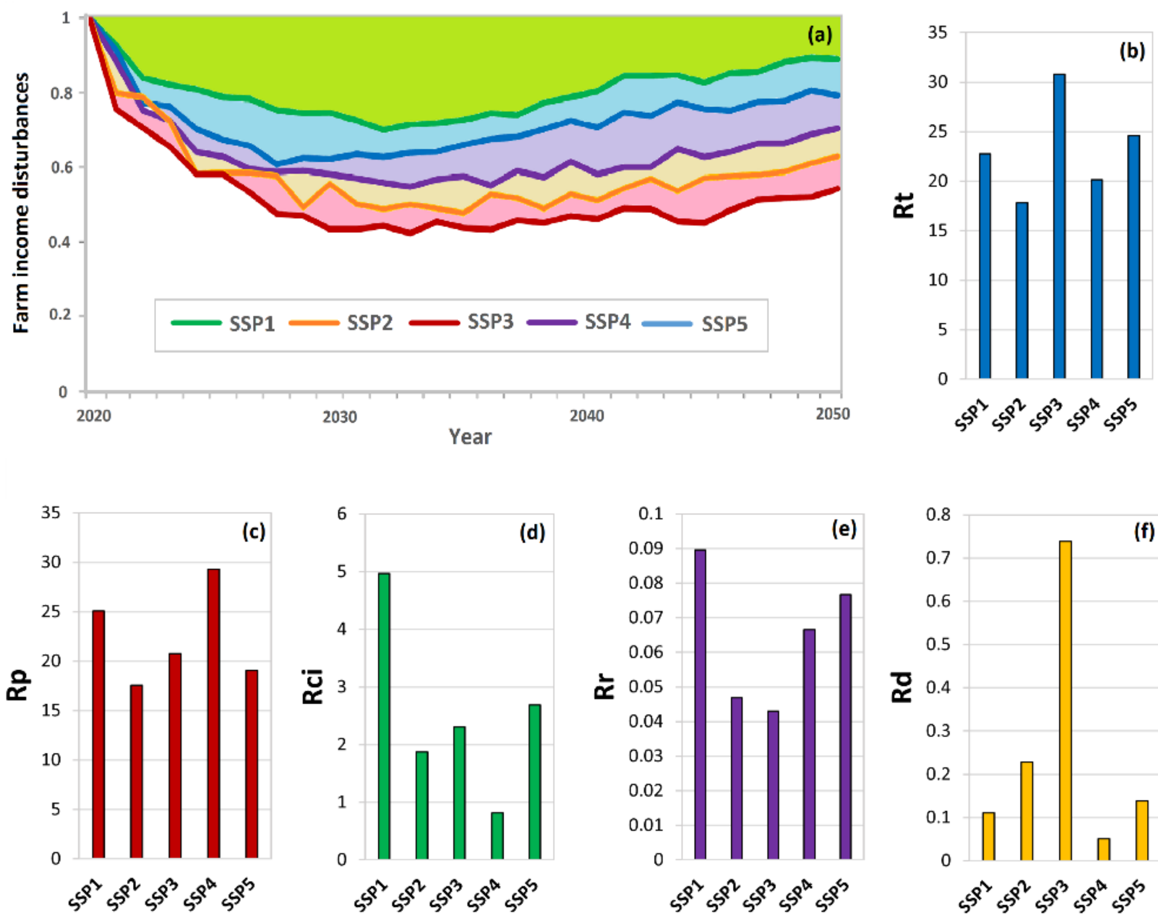

Figure 6.9 The transient behavior of farm income and corresponding resiliency metric values under various LSSP scenarios

6.4.4 Spatial Resiliency Analysis

It is important to assess regional resilience trends from multiple perspectives. A spatial analysis of trends within the region, demonstrated distinct differences in resiliency metrics depending on the watershed region and polygon networks of the area. An estimate of each resilience metric's value was calculated at the local level for each models' outcome. This spatial resilience study was undertaken to determine areas with the highest levels of resilience, *i.e.*, those with the least required adaptation. In turn, this facilitates an understanding of how trends and outcomes at various scales affect local system resilience (Cumming, 2011; Carper et al., 2021). Across the study area, resiliency metrics were not uniformly distributed for each of the model's output variables (Figure 6.10). A regional pattern was observed when the measurements of both study variables were compared under identical socioenvironmental LSSP settings. Western portions of the region experienced the most severe groundwater table conditions and, therefore, the greatest resilience sensitivity. Moreover, farm incomes and groundwater levels in the region are highly volatile and unstable. While resilience varied between the five metrics, Rd, Rr, and Rt remained relatively consistent for groundwater table and farm income, according to the spatial resilience analysis. Higher Rp and Rt values for farm income appear to be associated with lower resilience even though a discernible pattern does not emerge. The depth of the groundwater table in the northerly portion of the watershed showed the greatest resistance to socio-economic and climatic disturbances. There is a greater degree of disturbance, degree of return, and return time in the southern portion of the watershed, indicating a loss of resilience to socio-environmental and climate disturbance. There is also a great deal of vulnerability in the southwest portion of the watershed.

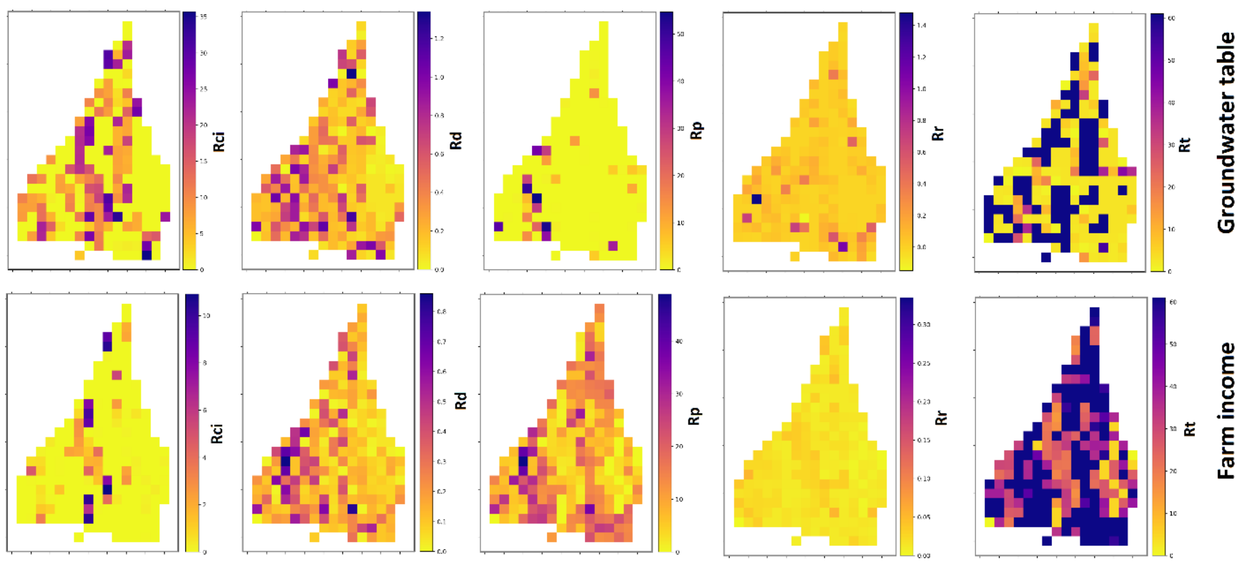

Figure 6.10 Spatial distribution of resiliency metrics across the study area for each model output variable.

6.5 Discussion

The LSSPs' socio-economic and climate change disturbances affected groundwater tables and agricultural income disproportionately. The groundwater table depth and farm income showed the greatest resilience and robustness (Figure 6.7) under shock scenarios for SSP1. There were greater susceptibility and suboptimal resilience measures for the groundwater table depth in each LSSP scenario (Figure 6.8), regardless of the perturbation type, duration, or severity. This apparent inherent tendency to sensitivity is attributable to the fact that the depth of the water table is a variable that is "slow," *i.e.*, responds to socio-environmental factors more slowly than other variables. The other socio-economic variable, farm income, demonstrated much greater variability in perturbation values as well as consistently large corrective impacts (Figure 6.9). In contrast, "fast" variables such as farm income have a greater ability to adjust in response to system-level perturbations and then return to their optimal position. Based on this trend, there is a tendency for farm income to be highly susceptible to regime shifts during times of stress. When changing to a new baseline of adaptability depending on different LSSP circumstances, there may be both a severe loss of functionality and major resilience performance failure.

The Rechna Doab's resilience indicators revealed that besides resilience varying among farms within the area's polygonal architecture, the regional trend of declining resilience does not follow a linear trajectory. Failure to adapt to a changing environment can be observed in regional trends under different SSPs. The spatial resilience displayed by the study variables is the result of a variety of environmental and socio-economic factors, including unequal water supply distributions between upper and lower watershed polygons (Figure 6.10). Aside from having more reliable access to fresh water, upper watershed farmers have also been incentivized to increase crop intensities by government subsidies, resulting in unsustainable depletion of groundwater resources, particularly in some other regions (Inam et al. 2015; Carper, 2021). Groundwater depletion in the southwest watershed regions exacerbates vulnerability to socio-environmental and climatic stress factors by diminishing their capacity for resilience. A large-scale application of the methods described in this study might be useful in estimating the resilience of human-water system operations.

The information and feedback from stakeholders used to develop the integrated model and LSSP scenarios considerably assisted in the comprehension of the human-water system's resilience and climate change adaptation capacity at the local scale. The proposed framework was created to discover whether the integrated modeling of resilience linked with robust optimization concepts could generate realistic solutions that could be used to assess resilience in real-life human-water systems. We highlighted the potential socio-hydrological resilience by focusing on three forms of modeling and framing, including integrated dynamic modeling, multi-scenario analysis, and multi-objective optimization (Liu et al., 2007; Gao et al., 2016). Considering human societies as inherent components of water cycles, this concept of integrated resilience modeling is vital to understanding how coupled human-water systems support and cope with disturbances (Ostrom, 2009; Mao et al., 2017). Highlighting the utility and integration of resilience with local/regional ecosystem services, we argued that multi-scenario multi-objective optimization offers a promising tool to characterize the robustness and resilience of coupled human-water systems.

In the context of LSSP scenarios analysis, combining concepts of multi-scenario multi-objective robust optimization with variable-level resilience quantification through stakeholder-informed integrated dynamic model constitutes a new contribution to the resilience-robustness literature (Walker et al. 2004; Mumby et al., 2014; Bizikova et al. 2017). In addition, the presently reported approaches and results are directly applicable and pertinent to the theory of robust-resilience, in which systems have the capacity to survive or adapt to adverse conditions (Walker et al., 2004; Janssen et al., 2007; Domptail and Easdale, 2013).

Decision makers could choose a strategy based on their final desired trade-off across resilience, robustness, and optimality indicators based on the Pareto optimal strategies offered by the present methodology. As various system designs are influenced by resilience and robustness, it is possible to develop solutions that perform well across both metrics. Using integrated dynamic modeling of resilience also facilitates the assignment of financial impacts (*e.g.*, farm income), to the environmental effects of groundwater depletion, the two variables that the current study examined.

6.6 Conclusions

Changing dynamics of water systems are largely influenced by human actions. Despite advances in coupled human-water systems, the complex interactions and feedback between human and environmental elements of water systems may push coupled systems beyond critical thresholds and cause in-system disruptions. A resilient systemic approach to coping with such conditions can be highly effective. Adaptive management based on resilient-robust policy design is fundamental, allowing flexible and easily adaptable strategies in the face of deep uncertainty surrounding future changes. When deep uncertainties exist, it is crucial that policy alternatives be evaluated in the light of increasing robustness and resilience. A novel multi-scenario-multi-objective optimization framework was introduced that can be used to evaluate the resilience-robustness of optimal solutions in adaptive management of coupled human-water systems under LSSP conditions. Integrating a set of appropriate resilience metrics with a suitable multi-scenario multi-objective robust optimization, we designed numerically efficient tools to aid decision-makers in balancing optimal resilience-enhancing robust solutions. The approach allows for a direct search for robust solutions, leading to optimal trade-offs with respect to the resilience of a system. In addition, the method can deal with the deep uncertainty involved in the solution search process. To illustrate its broad applicability, the proposed methodology was applied to the Rechna Doab watershed in Pakistan as a real-world coupled human-water system. Using a multi-scenario multi-objective framework to develop the integrated dynamic simulation-optimization model proposed in this study was very effective in assessing the resilience-robustness of the coupled human-water system under various socio-environmental and climatic stresses. The study demonstrates how simulation-based approaches can provide additional information in coupled human-water systems evaluations, contributing to the growing support for resiliency-robustness simulation-based assessments in the wake of deep uncertainty. The framework proposed in this study for assessing resilience will provide stakeholders and model users with a greater understanding of particular variables' vulnerabilities and adaptive capacities in coupled human-water systems. Despite focusing on human-water systems in Rechna Doab, we believe the proposed methodology of this study can be applied to other resilience practices for resilience-robustness contexts.

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CHAPTER 7: **Summary and Conclusions**

The main objective of this research was to develop, test, and apply a new ensemble multi-scenario multi-objective resilient-robust policy development framework for real-world coupled human-water systems applications. The main goal of this thesis was to demonstrate how the proposed resilient-robustness framework can be used to generate optimal, robust and resilient solutions for sustainable planning, which would prove very useful for supporting operational, management, and planning tasks commonly encountered by water resources managers. To demonstrate the usefulness of the method, the proposed framework was applied for assessing the vulnerabilities of Pakistan's Rechna Doab watershed as a real-world multi-stakeholder complex human-water system. It was shown to be successful, being able to capture the complex interactions of the systems variables and project the system performance under future scenarios.

Multi-scenario multi-objective resilient-robust policy development and integrated dynamic modeling framework of this research were primarily motivated by the complex, nonlinear, multiscale, and uncertain nature of coupled human-water systems that creates significant barriers for traditional optimization methods and often hampers their accuracy and reliability. A second motivating factor behind the development of the proposed models was related to the incorrect development of the majority of physically-based models in water resources that has led to some merely optimal-based solutions that cannot be used effectively in real-world water resources management applications. The proposed framework provided solutions to each of these obstacles. In particular, our framework addressed:

1. Complex interactions and nonlinearity, through the use of new integrated system dynamic model that is able to capture and simulate the behavioural dynamics of the human-water system and the complex relationships between its various elements.
2. Uncertainty through:
    - a storytelling approach in the context of participatory analysis integrated with probabilistic methods to extract uncertainties in both the physical and societal parts of the human-water system and,
    - a scenario discovery technique to explore different uncertainty spaces and see if there are prevailing storylines behind outcomes of interest
3. Resilient-robust optimal solutions through a multi-scenario multi-objective resilient-robust policy framework that not only considers optimality of the discovered solutions but also takes into the account their robustness and resiliency simultaneously.

This research was divided into four main parts (each resulting in peer-reviewed journal manuscripts). In the next four sub-sections, a summary and set of conclusions is given for each of the four components of this research.

7.1 Integrated Assessment of Localized SSP–RCP Narratives for Climate Change Adaptation in Coupled Human-Water Systems

Climate change impact and risk assessments need downscaled localized climate projections and context-relevant socio-economic scenarios. In this research, we have addressed this need using an integrated assessment of a localized SSP-RCP framework through an interdisciplinary and storyline development process that integrates bottom-up local expert-stakeholder knowledge with top-down insights from global SSPs. This study builds upon previous studies by simulating the localized SSP-RCP narratives using an integrated assessment model to produce spatial and temporal projections of variables of interest for quantifying potential natural resources hazards and vulnerabilities in a coupled human-water system. The proposed framework is notable for: (i) a storytelling approach to gather narratives for downscaling global SSPs to frame the hybrid local SSP-RCP narratives; (ii) a regional integrated system dynamic model developed with local stakeholders; and (iii) an assessment the impacts of a variety of profoundly uncertain socio-economic and climate scenarios on a multi-stakeholder human-water system in a developing country. The main findings of this study demonstrate that:

1. Incorporating global SSPs based on using climate scenarios as boundary conditions under different local conditions can help generate deep and practical determinations for formulating local extended SSPs.
2. Calibrating global models with regional scenarios helped to balance local narratives with global perspectives.
3. Regional integrated models can provide for a rigorous evaluation and quantification of global SSP-RCP narratives.
4. The Rechna Doab human-water system is not water secure. According to the projections based on some local SSP scenarios (SSP1, SSP5, SSP4), with slightly greater rates of technological improvement (particularly in the agricultural sector), along with better policies, institutions, and environmental awareness, only slight increases in farm income and crop yields are likely.
5. Stakeholder values could be used to generate meaningful scales without requiring additional assumptions in analyses of coupled human-water systems. It also facilitates communication and understanding between modeler- and stakeholder-led communities and integrates qualitative and quantitative methodologies using multiple uncertainty concepts.

7.2 Scenario Analysis of Local Storylines to Represent Uncertainty in Complex Human-Water Systems

This study proposed a transdisciplinary approach that integrated social and environmental sciences to characterize and comprehend uncertainty in the dynamic interactions of key factors affecting human-water systems. This study introduced a novel framework for representing uncertainty through linguistic and epistemic uncertainty quantification using storyline narratives in the context of regional integrated dynamic models. An integrated dynamic model developed with stakeholders was used to support and test a framework to quantify the uncertainty of a human-water system under a range of socio-economic and climate changes processes. Using probability-based sampling from each integrated model's input variables, the study quantified and analyzed the uncertainty of desired outputs of the integrated model to represent uncertainty in the narrative storylines. Finally, a different application of scenario discovery techniques was applied to uncertainty ensembles to explore the relationship between outcome variables of interests and to discover cohesive storylines of interest. Analyses provide insight into uncertainty in integrated assessment modeling of coupled human-water systems. Based on the findings of this study, the following conclusions were drawn:

1. Using event-oriented rather than probability-based storylines can increase risk awareness because people better understand longer-term events, such as trends, which is more in line with how they perceive and react to risk.
2. As a decision-support tool, narratives may be particularly beneficial for integrating climate change information with other pertinent factors in order to manage compound risk and build suitable stress tests for a particular vulnerability.
3. The use of storylines may act as a physical basis for dividing uncertainty, which permits the use of regional models under certain conditions.
4. In addition, narratives may reach beyond the limitations of standard models to explore the limits of plausibility, thus avoiding false precision and surprise

This information is vital in creating a more complete picture of uncertainty analysis in coupled human-water systems and to inform the climate change community to consider narrative approaches more effectively.

7.3 Multi-scenario Multi-Objective Analysis of Robust Policy Development in Human-Water Systems Under Deep Uncertainty

This research introduced a novel framework for scenario analysis of downscaled SSP narratives to examine the feasibility and robustness of water resources adaptation policies depending on localized SSPs conditions. An integrated dynamic simulation-optimization model that simulates the vulnerabilities of the complex human-water system was developed to identify robust policies that function well under a set of downscaled SSPs. The developed integrated dynamic model also considered deep uncertainty in the optimization phase to ensure robust optimal solutions. The performance of solutions was evaluated in the integrated dynamic simulation-optimization model in terms of all objectives in a set of localized SSP scenarios. As a result, Pareto-optimal solutions were 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 multi-scenario, multi-objective decision-making problem evaluated candidate policies. Based on the findings of this study, the following conclusions were drawn:

1. Integrating a multi-scenario multi-objective analysis (meta-criteria analysis) of a set of downscaled SSP storylines with the multi-objective robust decision-making concept can help to find robust optimal solutions under deep uncertainty concerning regional climate adaptation.
2. Diverse socio-environmental variables of a series of localized SSP scenarios might influence the robustness of policy options in various capacities.

7.4 Resilience-Based Robust Policy Design for Coupled Human-Water Systems

This study developed a multidisciplinary framework on how the concepts of robustness and resiliency analysis within multi-scenario multi-objective optimization analysis (meta-criteria analysis), can be integrated to facilitate the development of adaptation policies that are optimal, robust, and resilient in dealing with deep uncertainty related to localized SSP scenarios in a coupled human-water system. Five resilient objective functions based on system resilience were explored during the model's optimization search. A resilience assessment was then conducted on various system variables, including farm income and groundwater table (*i.e.*, the extent to which certain variables respond to socio-economic and climate disturbances and adaptation conditions under the SSP scenarios). Based on the findings of this study, the following conclusions were drawn:

1. The proposed framework was highly effective in assessing the resilience-robustness of the human-water system under various socio-environmental and climatic stresses. The study demonstrates how simulation-optimization-based approaches can provide additional information in human-water systems evaluations, contributing to the growing support for resiliency-robustness simulation-based assessments in the face of deep uncertainty.
2. The approach allows for a direct search for robust solutions, leading to optimal trade-offs with respect to the resilience of a system. In addition, the method was capable of dealing with the deep uncertainty involved in the solution search.

3. The framework provided stakeholders and model users with a greater understanding of particular variables' vulnerabilities and adaptive capacities in coupled human-water systems.
4. The Rechna Doab's resilience indicators revealed that in addition to varying resilience across the area, the trend of declining resilience in the region does not follow a linear trajectory.

In response to the fundamental questions of this study, the following conclusions can be drawn based on the general overview of this study's findings and the interconnected outcomes of all four research objectives:

First, the findings of merging top-down and bottom-up techniques in Chapter 4 demonstrated that including stakeholder input in scenario development is crucial and aided significantly in achieving a balance between global and local scenarios. As a result of the SSP-RCP framework that was utilized, both mitigation and adaptation challenges, as well as the narratives of stakeholders, played a crucial part in the design of local SSPs. The results of Chapter 5 demonstrated that stakeholder input could combine linguistic and epistemic uncertainty analysis, provide realistic ranges, and possibly replace expert judgment for individual drivers that influenced the dynamics of socio-economic and environmental change in a real-world human-water system. The results of Chapter 6 demonstrated that SSP scenarios might be understood in the context of robust policymaking by analyzing the effect of scenario variety on the robustness values and ranking of policy alternatives. In order to inform robust regional decision-making, a broader diversity of candidate solutions within the scope of the suggested strategy allowed for the possibility to prioritize objectives or agree on acceptable levels of trade-offs. The results of Chapter 7 demonstrated that the information and comments from stakeholders utilized to construct the integrated model and LSSP scenarios significantly aided in the understanding of the resilience and climate change adaptation capacity of the human-water system at the local scale. This concept of integrated resilience modeling contributed to understanding how coupled human-water systems support and adapt to disruptions.

Moreover, given the context of human-water systems in the study area, the results indicate:
The human water system of Rechna Doab is not water secure. According to projections based on some local SSP scenarios, even with slightly higher rates of technological advancement (particularly in the agricultural sector) and improved policies, institutions, and environmental awareness, farm income and crop yields are only likely to increase slightly. However, due to a growing population, shifting consumption patterns, and the shift toward a growing economy dependent on agriculture, water demands are expected to remain a major challenge for the area. Groundwater depletion uncertainty was greatest in the southern portion of the Rechna Doab watershed, specifically in the

Lahore and Punjab regions, where agricultural activity and irrigation consumption are most uncertain due to climate uncertainty and socio-economic conditions. Socio-economic and climate change disturbances caused by different conditions of localized SSPs- had a disproportionate impact on groundwater tables and agricultural income. The robustness of policy solutions was significantly affected by the interaction between the selected local narratives and the collection of SSP scenarios, as well as the socio-environmental conditions of the system performance metric (e.g., adaptability) over the region. Indicators of resilience in the Rechna Doab revealed that, in addition to variations in resilience amongst uncertain variables, the regional trend of falling resilience did not follow a linear trajectory. Regional patterns governed by several SSPs exhibit a lack of capacity to adapt to a changing environment.

CHAPTER 8: **Contributions to Knowledge and Recommendations for Future Research**

8.1 Contributions to Knowledge

A new multi-scenario multi-objective framework has been developed that can dynamically simulate coupled human-water interactions and facilitate the exploration and recommendation of optimal resilient-robust solutions under deep uncertainty related to regional socio-environmental and climate change. The main contributions of this dissertation are outlined below:

1. Developing a new stepwise procedure for developing downscaled localized SSP-RCP scenarios through linking local stakeholders' storyline narratives with global SSP as boundary conditions by using transdisciplinary approaches such as storytelling. The proposed approach served to increase the understanding of how: (i) calibrating global models with regional scenarios can help balance local narratives with global perspectives, (ii) regional integrated models can provide for a rigorous evaluation and quantification of SSP-RCP narratives and, (iii) in the context of developing countries, the implications of future climate change and socio-economic uncertainty regarding water resources and the environment of human-water systems can be identified.
2. Developing a new framework for systematic exploration of uncertainty space and quantification of linguistic and epistemic uncertainty in coupled human-water systems by integrating storyline narratives, fuzzy sets, and low discrepancy sequences probabilistic sampling methods in the context of a regional integrated dynamic model.
3. Revealing a different application of scenario discovery techniques to uncertainty ensembles to explore the relationship between systems' social and environmental variables of interest (e.g., farm income and groundwater depth) and other outcomes and to discover cohesive storylines of interest.
4. Bridging the literature on multi-scenario analysis (meta-criteria analysis) of downscaled/localized SSP scenarios with the literature on multi-objective robust decision-making to understand the effect of deep uncertainty on the robustness values of various policy alternatives within the context of localized SSP scenarios.
5. Developing a novel resilience-based multi-scenario multi-objective robust optimization framework to find optimal resilient-robust solutions under various socio-economic and climate disturbances related to a set of downscaled shared socio-economic pathways (SSP) scenarios.

8.2 Recommendations for Future Research

1. In developing the localized SSP-RCPs scenarios, drawing on narratives and trend indicators, this study followed the one-to-one mapping method to map the global SSP narratives onto the local narrative scenarios. Interesting further steps might include exploring more process-based techniques capable of better quantification of social knowledge, to link the stakeholders' narratives and global scenarios.
2. In this study, an integrated system dynamic modeling approach was used for simulating dynamic interactions between human and water system. Although this approach offers several advantages to examine the behavioural dynamics of the human-water system and the complex relationships between its various elements, it is sometimes very complex, with a variety of social and environmental factors to be considered. Developing methods based on machine learning approaches could be an effective alternative to be explored for capturing the complex interactions of the system.
3. Due to the complex nature of the socio-economic and environmental system, simplified model assumptions and unavailability of data, especially for socio-economic components, a detailed uncertainty and sensitivity analysis procedure for the integrated model is needed. This procedure would use the information gained during stakeholder interviews and a comprehensive literature review to assign standard deviations to highly uncertain exogenous model parameters for uncertainty and sensitivity analysis. Such a procedure would help in robust decision-making by addressing the sources of vulnerability.
4. The proposed framework focused on the resiliency and robustness of optimal candidate solutions using multi-scenario multi-objective optimization. Other sustainability performance assessments such as flexibility, reliability, etc. would be interesting to include in the analysis.
5. To quantify the degree of resilience under each unique socio-economic perturbations in the human-water system, five criteria, each representing a different characteristic of a resilient reaction to perturbations were applied. It would be interesting to consider more residency metrics to assess how efficiently variables can recover from disturbances, and accounting for the possibility that variables won't be able to regain their pre-disruption functional equilibrium.