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Integrated assessment of localized SSP–RCP narratives for climate change adaptation in coupled human-water systems

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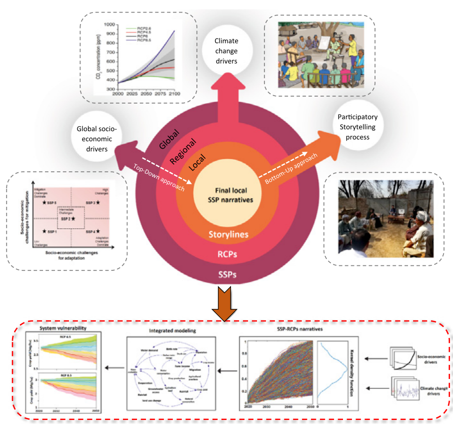
HIGHLIGHTS

- A localized hybrid SSP-RCP scenario framework is designed at a regional/local scale.
- Storytelling is used to link bottom-up local knowledge and top-down insights from SSPs.
- Regional integrated assessment modeling quantifies climate change implications.
- The concept informs climate adaptation at regional scales for developing countries.
- SSP3 and SSP2 would aggravate water security and environmental deterioration.

GRAPHICAL ABSTRACT



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ABSTRACT

The assessment of climate change impacts requires downscaled climate projections and context-specific socioeconomic 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 of a localized hybrid Shared Socioeconomic 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 use 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 dynamics 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 scenario narratives,

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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.

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 and Kim (2021) evaluated the influence of climatic and socioeconomic 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 modeling 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 dynamics 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 dynamics 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.

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 (Fig. 1). Located in Pakistan's portion of the Indus Plain, the watershed covers roughly 732.5 km^2 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 160×10^3 km^2 and drawing upon 128 km^3 yr^{-1} in water diversion (Ahmad, 2002; Inam et al., 2017a, 2017b). 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, 2017b).

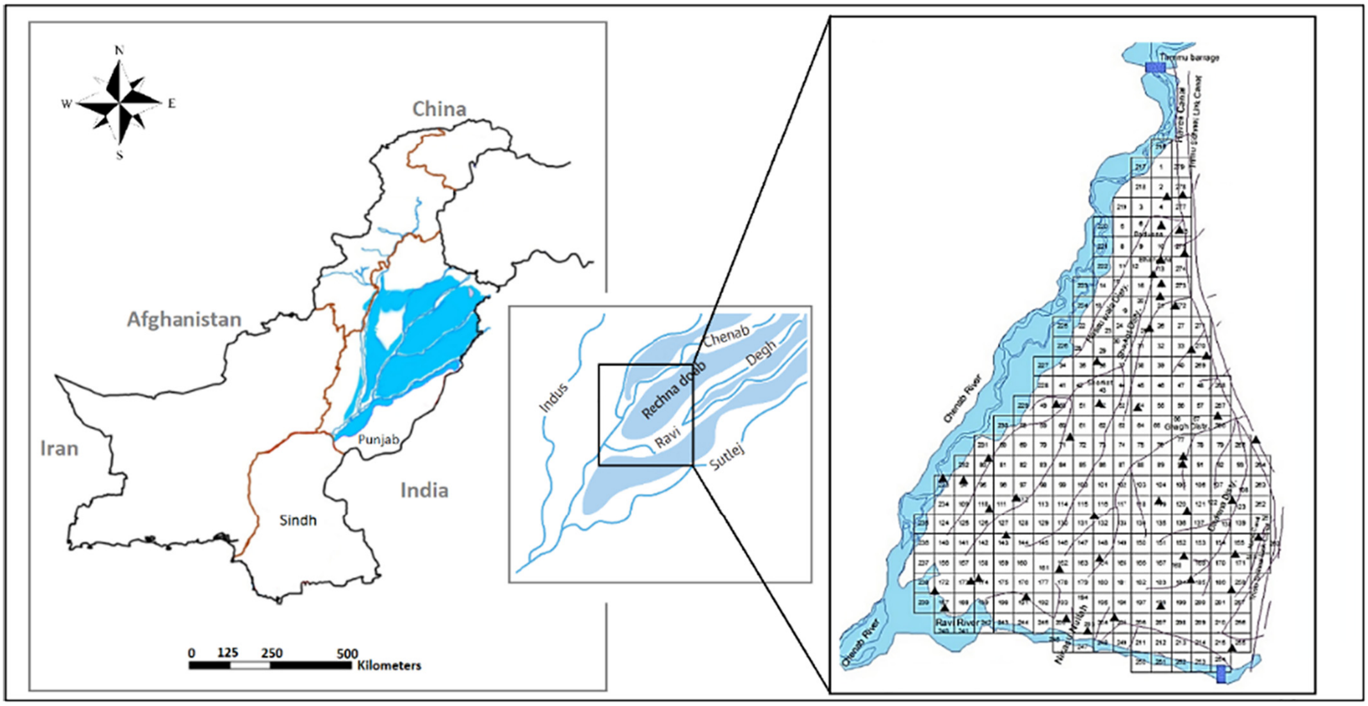


Fig. 1. Study area in Pakistan's Rechna Doab basin.

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 resources management (Table S3 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.

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 scenario 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 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 dynamic interactions overlooked in prior research on human-water systems. Fig. 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.

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., 2020;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 SSPs 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., 2020). 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.

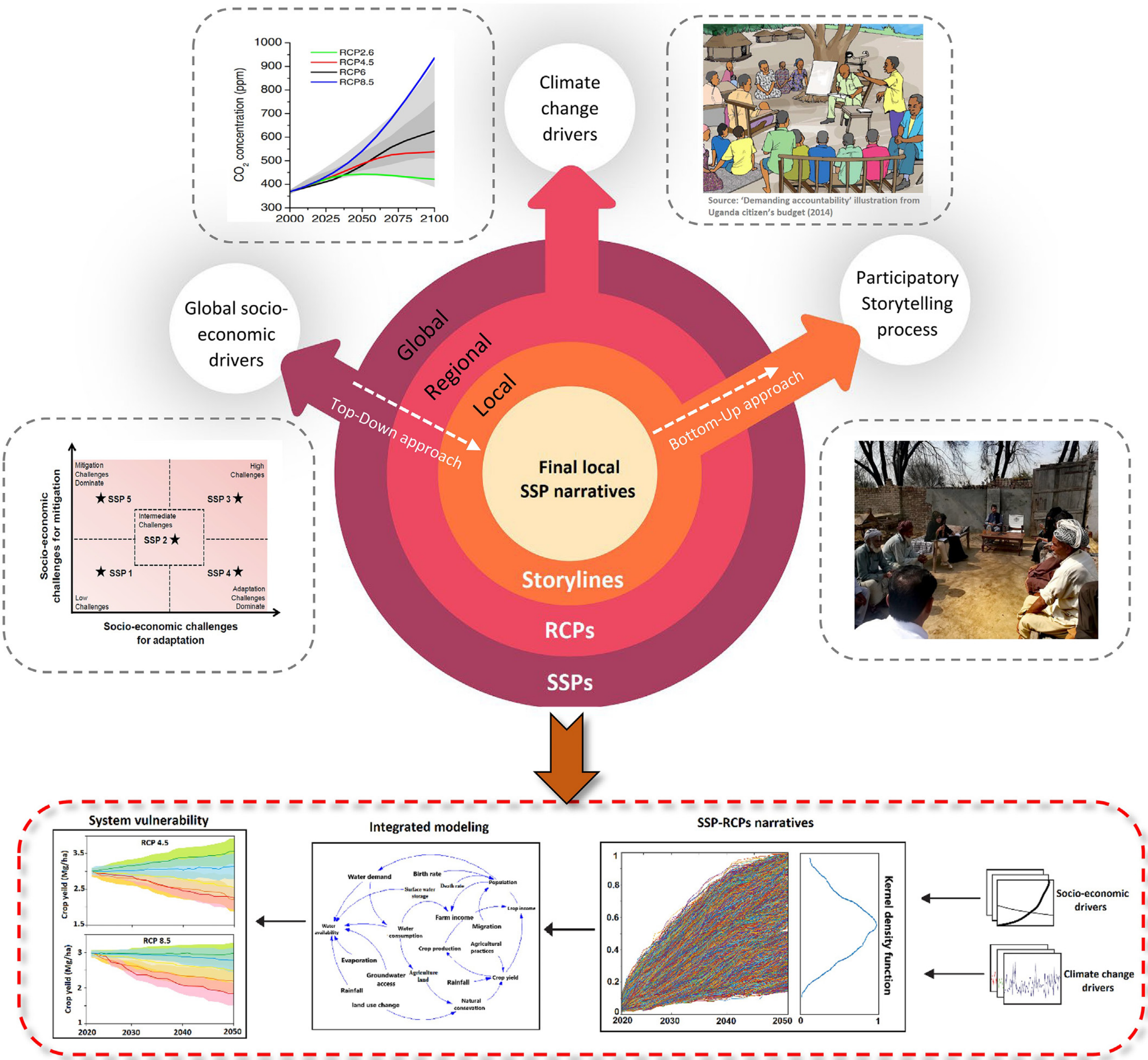


Fig. 2. The Integrated scenario framework based on a localized hybrid SSP-RCP framework and participatory storytelling methods.

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; Perrone et al., 2020) that included: (i) problem definition, (ii) stakeholder analysis, (iii) individual interviews and causal loop diagram (CLD) development, (iv) building one group CLD, and (v) simplifying the merged CLD 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 and Henrichs, 2008; Rounsevell and 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 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, 2017b). 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.

Table 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

Note: 0 indicates no change; +/+ + indicate low/high increase; and −/− − indicate low/ high decrease compared to the baseline.

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-20th 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 S1), 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 S2). 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 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 SSP 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. Regional integrated socio-economic and environmental system dynamics model (ISESD)

The regional integrated socio-economic and environmental system dynamics 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) developed by Inam, Adamowski, and Malard (Inam et al., 2017a, 2017b; 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., 2017a, 2017b; Malard et al., 2017). Furthermore, the integrated socio-economic system dynamics 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, Fig. 3 displays some of the components of submodules of the regional ISESD model.

4. Results

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 S1). Table 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.

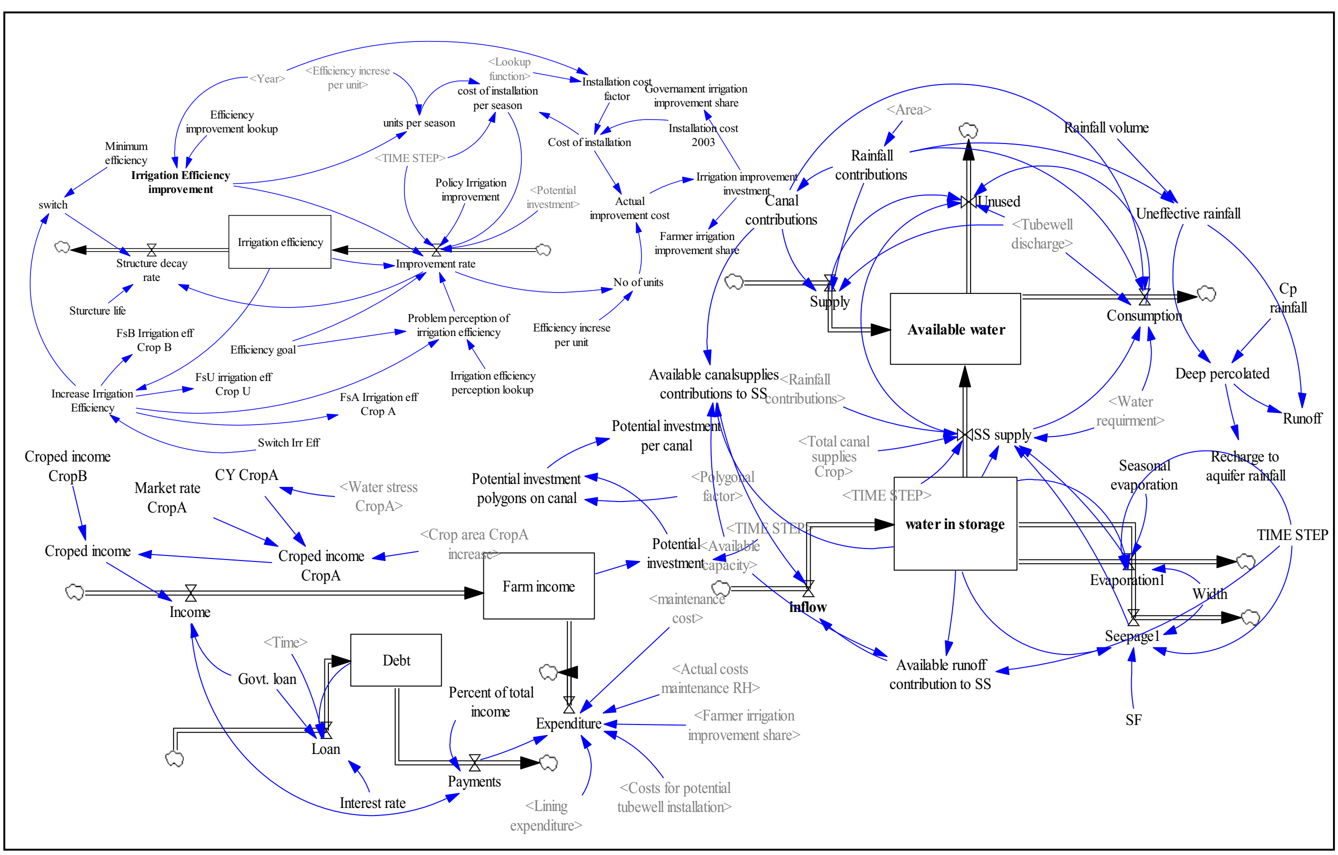


Fig. 3. Some main submodules of the integrated socio-economic and environmental system dynamic (ISESD) model structure.

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

4.1.1. 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 resources 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).

4.1.2. 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.

4.1.3. 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 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.

4.1.4. 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.

4.1.5. 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 process, stakeholders provided their ideas about how future changes might impact Rechna Doab economically, environmentally, and 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, Fig. 4 displays the relative importance of each local SSP element, as assessed by the stakeholders. While environmental and natural resources issues, including climate change, were the most prominent, other issues were also highlighted, especially economics, policies, and institutions.

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 1; Table S1 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

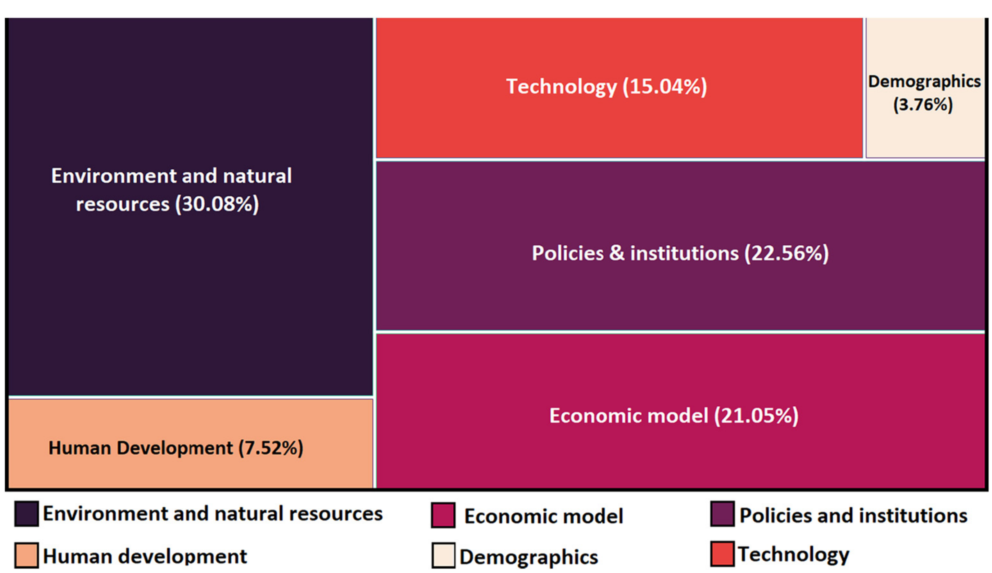


Fig. 4. Relative importance of each element of local SSPs, based on stakeholder opinions.

of climate change. The results of these analyses are discussed in the following sections.

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 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 (Fig. 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 (Fig. 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

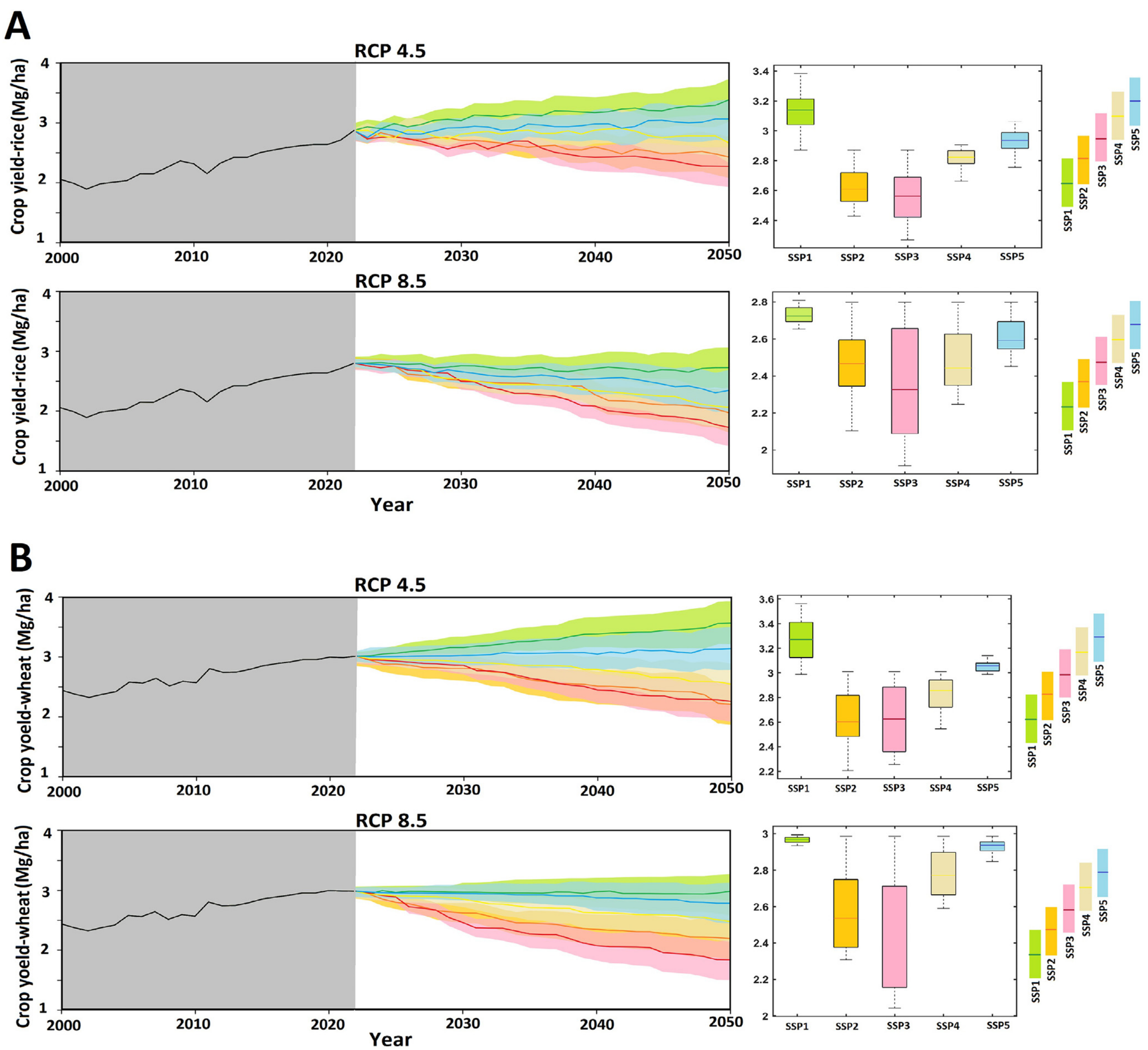


Fig. 5. Projected changes in crop yields under different SSP-RCPs.

19.3% under localized SSP5 and SSP1 scenarios, respectively (Fig. 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., 2018).

4.2.2. Changes in farm income and economy

To explore the effects of macro drivers of localized SSP-RCP scenarios on economic and environmental outcomes, SSP-RCP future scenarios were modeled using the regional integrated model for 30-year simulations from the base year of 2020. Fig. 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 (Fig. 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 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.

4.2.3. Projected impacts on water demands

Fig. 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 forecasted to occur under some of the SSP scenarios (e.g., SSP1, SSP5, SSP4), it will be difficult to meet such increased water demands with the present form of agriculture.

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 (Fig. 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

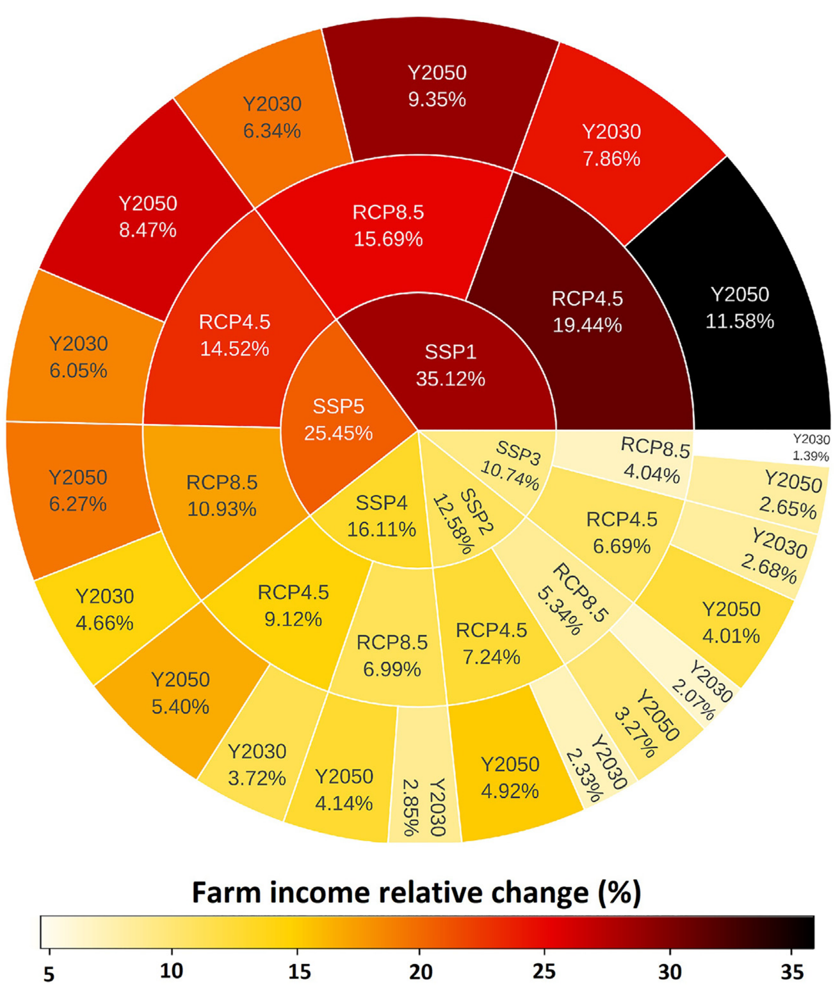


Fig. 6. Relative change of farm income under different SSP-RCP scenarios.

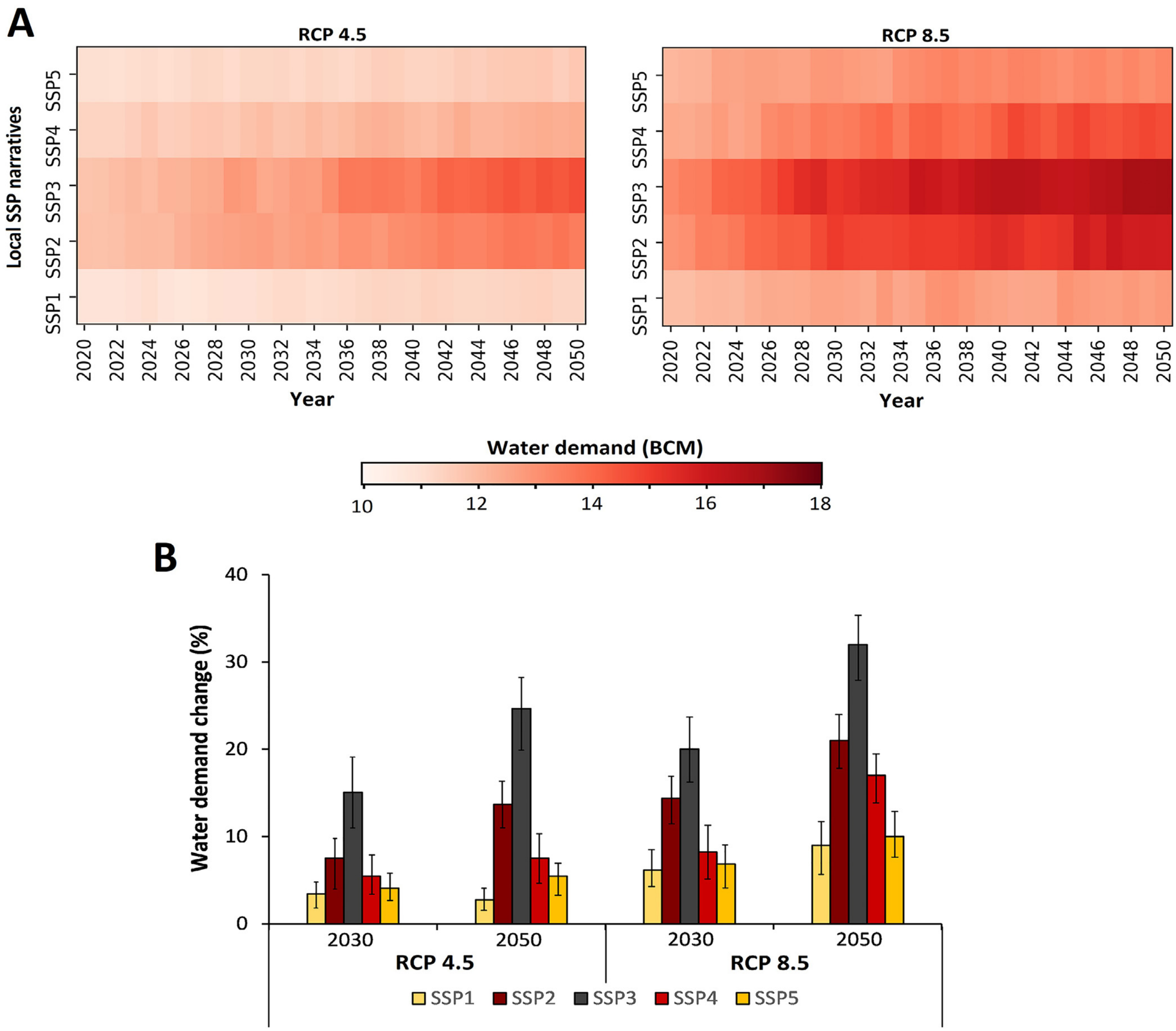


Fig. 7. Water demands increase under local hybrid SSP-RCPs scenarios.

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.

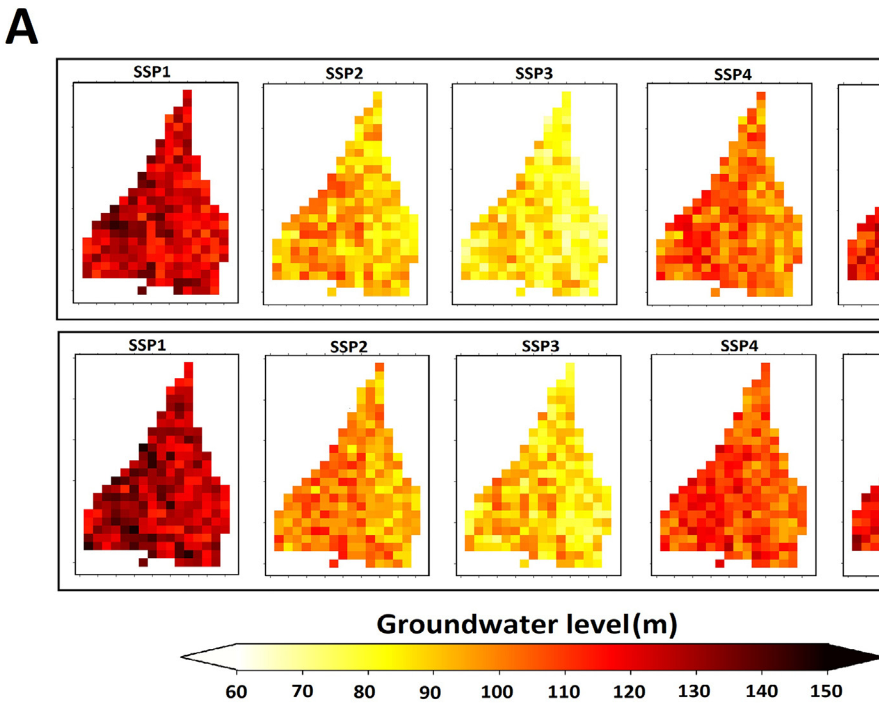
4.2.4. Projected impacts on groundwater resources

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 (Fig. 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 the Punjab.

Under different climate change and socio-economic scenarios, groundwater depletion would worsen by 2030 and mid-century periods (Fig. 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.

5. Discussion

By combining top-down and bottom-up approaches, we developed five semi-quantitative local SSP scenarios for the human-water system of the Rechna Doab region of Pakistan. Global SSPs were used as a basis for developing localized SSPs using local narrative storyline SSPs and providing a regional interpretation. The basic concepts of the localized SSPs are summarized in Table 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



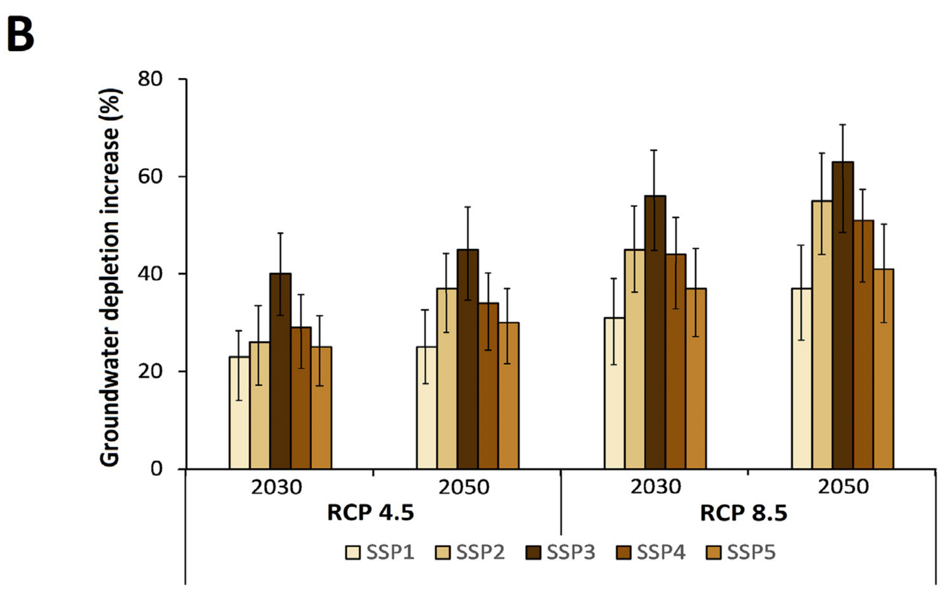


Fig. 8. Spatial changes in groundwater level in the Rechna Doab basin under SSP-RCP scenarios by 2050.

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 and 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 (Özkaynak & 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 point 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 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 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 sometimes 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 storytelling, emphasizing its potential for participatory stakeholder engagement in climate adaptation for coupled human-water systems, as well as raising awareness of future challenges. In our study, 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.

6. Conclusion

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.

Credit: authorship contribution statement

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

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Absar, S.M., Preston, B.L., 2015. Extending the shared socio-economic pathways for sub-national impacts, adaptation, and vulnerability studies. Glob. Environ. Chang. 33, 83–96.

Ahmad, M.U.D., 2002. Estimation of Net Groundwater Use in Irrigated River Basins Using Geo-information Techniques: A Case Study in Rechna Doab, Pakistan. Wageningen University, Wageningen, The Netherlands Doctoral dissertation.

Ahmad, A., Ashfaq, M., Rasul, G., Wajid, S.A., Khaliq, T., Rasul, F., Saeed, U., Rahman, M.H. U., Hussain, J., Ahmad Baig, I., Naqvi, S.A.A., 2015. Impact of climate change on the rice–wheat cropping system of Pakistan. Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project Integrated Crop and Economic Assessments, pp. 219–258 Part 2.

Alcamo, J., 2008. Chapter six. The SAS approach: combining qualitative and quantitative knowledge in environmental scenarios. Developments in Integrated Environmental Assessment. 2, pp. 123–150. https://doi.org/10.1016/S1574-101X(08)00406-7.

Alcamo, J., Henrichs, T., 2008. Chapter 2. Towards guidelines for environmental scenario analysis. Developments in Integrated Environmental Assessment. 2, pp. 13–35.

Alizadeh, M.R., Adamowski, J.F., Inam, A., Malard, J.J., 2020. Integrating storytelling and a coupled socio-economic and environmental models to explore interactions, uncertainties and vulnerabilities of complex human-water systems. DecemberAGU Fall Meeting Abstracts. Vol. 2020 pp. SY039-03.

Alizadeh, M., Adamowski, J., Inam, A., 2021. Linking stakeholder scenarios and shared socio-economic pathways for policy making in human-water systems. AprilEGU General Assembly Conference Abstracts (pp. EGU21-8132).

Allan, A., Barbour, E., Nicholls, R.J., Hutton, C., Lim, M., Salehin, M., Rahman, M.M., 2021. Developing socio-ecological scenarios: a participatory process for engaging stakeholders. Sci. Total Environ. 150512.

Arshad, A., Zhang, Z., Zhang, W., Gujree, I., 2019. Long-term perspective changes in crop irrigation requirement caused by climate and agriculture land use changes in rechna doabPakistan. Water 11 (8), 1567.

Berkhout, F., Hertin, J., 2002. Foresight futures scenarios: developing and applying a participative strategic planning tool. Greener Manag. Int. 37, 37–52.

Biggs, R., Raudsepp-Hearne, C., Atkinson-Palombo, C., Bohensky, E., Boyd, E., Cundill, G., Fox, H., Ingram, S., Kok, K., Spehar, S., Tengö, M., 2007. Linking futures across scales: a dialog on multiscale scenarios. Ecol. Soc. 12 (1), 17.

Booth, E.G., Qiu, J., Carpenter, S.R., Schatz, J., Chen, X., Kucharik, C.J., Loheide II, S.P., Motew, M.M., Seifert, J.M., Turner, M.G., 2016. From qualitative to quantitative environmental scenarios: translating storylines into biophysical modeling inputs at the watershed scale. Environ. Model Softw. 85, 80–97.

Carlsen, H., Klein, R.J., Wikman-Svahn, P., 2017. Transparent scenario development. Nat. Clim. Chang. 7 (9), 613.

Carper, J., Alizadeh, M.R., Adamowski, J., Inam, A., Malard, J., 2021. Quantifying the transient shock response of dynamic agroecosystem variables for improved socio-environmental resilience. Ecol. Soc. 26 (2), 17.

Challinor, A.J., Adger, W.N., Benton, T.G., 2017. Climate risks across borders and scales. Nat. Clim. Chang. 7 (9), 621–623.

Chen, Y., Liu, A., Zhang, Z., Hope, C., Crabbe, M.J.C., 2019. Economic losses of carbon emissions from circum-Arctic permafrost regions under RCP-SSP scenarios. Sci. Total Environ. 658, 1064–1068.

Ebi, K.L., Hallegatte, S., Kram, T., Arnell, N.W., Carter, T.R., Edmonds, J., Kriegler, E., Mathur, R., O'Neill, B.C., Riahi, K., Winkler, H., 2014. A new scenario framework for climate change research: background, process, and future directions. Clim. Chang. 122 (3), 363–372.

Frame, B., Lawrence, J., Ausseil, A.G., Reisinger, A., Daigneault, A., 2018. Adapting global shared socio-economic pathways for national and local scenarios. Clim. Risk Manag. 21, 39–51.

Frantzeskaki, N., Hölscher, K., Holman, I.P., Pedde, S., Jaeger, J., Kok, K., Harrison, P.A., 2019. Transition pathways to sustainability in greater than 2°C climate futures of Europe. Reg. Environ. Chang. 19 (3), 777–789.

Gorst, A., Dehlavi, A., Groom, B., 2018. Crop productivity and adaptation to climate change in Pakistan. Environ. Dev. Econ. 23 (6), 679–701.

Graham, N.T., Hejazi, M.I., Chen, M., Davies, E.G., Edmonds, J.A., Kim, S.H., Turner, S.W., Li, X., Vernon, C.R., Calvin, K., Miralles-Wilhelm, F., 2020. Humans drive future water scarcity changes across all shared socioeconomic pathways. Environ. Res. Lett. 15 (1), 014007.

Halbe, J., Pahl-Wostl, C., Adamowski, J., 2018. A methodological framework to support the initiation, design and institutionalization of participatory modeling processes in water resources management. J. Hydrol. 556, 701–716.

Harrison, P.A., Dunford, R.W., Holman, I.P., Cojocaru, G., Madsen, M.S., Chen, P.Y., Pedde, S., Sandars, D., 2019. Differences between low-end and high-end climate change impacts in Europe across multiple sectors. Reg. Environ. Chang. 19 (3), 695–709.

Hazeleger, W., van den Hurk, B.J., Min, E., van Oldenborgh, G.J., Petersen, A.C., Stainforth, D. A., Vasileiadou, E., Smith, L.A., 2015. Tales of future weather. Nat. Clim. Chang. 5 (2), 107–113.

Inam, A., Adamowski, J., Halbe, J., Prasher, S., 2015. Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: a case study in the Rechna Doab watershed, Pakistan. J. Environ. Manag. 152, 251–267.

Inam, A., Adamowski, J., Prasher, S., Halbe, J., Malard, J., Albano, R., 2017a. Coupling of a distributed stakeholder-built system dynamics socio-economic model with SAHYSMOD for sustainable soil salinity management–part 1: model development. J. Hydrol. 551, 596–618.

Inam, A., Adamowski, J., Prasher, S., Halbe, J., Malard, J., Albano, R., 2017b. Coupling of a distributed stakeholder-built system dynamics socio-economic model with SAHYSMOD for sustainable soil salinity management. Part 2: model coupling and application. J. Hydrol. 551, 278–299.

Iqbal, M.S., Islam, M.M., Hofstra, N., 2019. The impact of socio-economic development and climate change on E. Coli loads and concentrations in Kabul River,Pakistan. Sci. Total Environ. 650, 1935–1943.

Kebede, A.S., Nicholls, R.J., Allan, A., Arto, I., Cazcarro, I., Fernandes, J.A., Hill, C.T., Hutton, C.W., Kay, S., Lázár, A.N., Macadam, I., 2018. Applying the global RCP–SSP–SPA scenario framework at sub-national scale: a multi-scale and participatory scenario approach. Sci. Total Environ. 635, 659–672.

Kok, K., van Vliet, M., 2011. Using a participatory scenario development toolbox: added values and impact on quality of scenarios. J. Water Clim. Chang. 2 (2–3), 87–105.

Kok, K., Pedde, S., Gramberger, M., Harrison, P.A., Holman, I.P., 2019. New European socio-economic scenarios for climate change research: operationalising concepts to extend the shared socio-economic pathways. Reg. Environ. Chang. 19 (3), 643–654.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R.J., Moss, R.H., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. Glob. Environ. Chang. 22 (4), 807–822.

Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K.L., Kram, T., Riahi, K., Winkler, H., Van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared climate policy assumptions. Clim. Chang. 122 (3), 401–414.

Kunseler, E.M., Tuinstra, W., Vasileiadou, E., Petersen, A.C., 2015. The reflective futures practitioner: balancing salience, credibility and legitimacy in generating foresight knowledge with stakeholders. Futures 66, 1–12.

Malard, J.J., Inam, A., Hassanzadeh, E., Adamowski, J., Tuy, H.A., Melgar-Quiñonez, H., 2017. Development of a software tool for rapid, reproducible, and stakeholder-friendly dynamic coupling of system dynamics and physically-based models. Environ. Model Softw. 96, 410–420.

Mehboob, M.S., Kim, Y., 2021. Effect of climate and socioeconomic changes on future surface water availability from mountainous water sources in Pakistan's upper Indus Basin. Sci. Total Environ. 769, 144820.

Mitter, H., Techen, A.K., Sinabell, F., Helming, K., Kok, K., Priess, J.A., Schmid, E., Bodirsky, B. L., Holman, I., Lehtonen, H., Leip, A., 2019. A protocol to develop shared socio-economic pathways for European agriculture. J. Environ. Manag. 252, 109701.

Moezzia, M., Kathryn, B.J., Rotmann, Sea, 2017. Using stories, narratives, and storytelling in energy and climate change research.

Nilsson, A.E., Bay-Larsen, I., Carlsen, H., van Oort, B., Bjørkan, M., Jylhä, K., Klyuchnikova, E., Masloboev, V., van der Watt, L.M., 2017. Towards extended shared socio-economic pathways: a combined participatory bottom-up and top-down methodology with results from the Barents region. Glob. Environ. Chang. 45, 124–132.

O'Neill, B.C., Carter, T.R., Ebi, K., Harrison, P.A., Kemp-Benedict, E., Kok, K., Kriegler, E., Preston, B.L., Riahi, K., Sillmann, J., van Ruijven, B.J., 2020. Achievements and needs for the climate change scenario framework. Nat. Clim. Chang. 10 (12), 1074–1084.

O'Neill, B.C., Tebaldi, C., Vuuren, D.P.V., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.F., Lowe, J., Meehl, G.A., 2016. The scenario model intercomparison project (ScenarioMIP) for CMIP6. Geosci. Model Dev. 9 (9), 3461–3482.

Özkaynak, B., Rodríguez-Labajos, B., 2010. Multi-scale interaction in local scenario-building: a methodological framework. Futures 42 (9), 995–1006.

Pedde, S., Harrison, P.A., Holman, I.P., Powney, G.D., Lofts, S., Schmucki, R., Gramberger, M., Bullock, J.M., 2021. Enriching the shared socio-economic pathways to co-create consistent multi-sector scenarios for the UK. Sci. Total Environ. 756, 143172.

Perrone, A., Inam, A., Albano, R., Adamowski, J., Sole, A., 2020. A participatory system dynamics modeling approach to facilitate collaborative flood risk management: a case study in the Bradano River (Italy). J. Hydrol. 580, 124354.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., Hasegawa, T., 2017. Land-use futures in the shared socio-economic pathways. Glob. Environ. Chang. 42, 331–345.

Reed, M.S., Kenter, J., Bonn, A., Broad, K., Burt, T.P., Fazey, I.R., Fraser, E.D.G., Hubacek, K., Nainggolan, D., Quinn, C.H., Stringer, L.C., 2013. Participatory scenario development for environmental management: a methodological framework illustrated with experience from the UK uplands. J. Environ. Manag. 128, 345–362.

Rehman, G., Munawwar, H.Z., Hussain, A., 1997. History of irrigated agriculture: a selected appraisal. Salinity Management Alternatives for the Rechna Doab, Punjab, Pakistan. Research Report No. R-21.2Volume-II. International Irrigation Management Institute (IIMI), Lahore, Pakistan 145pp.

Reimann, L., Vollstedt, B., Koerth, J., Tsakiris, M., Beer, M., Vafeidis, A.T., 2021. Extending the shared socio-economic pathways (SSPs) to support local adaptation planning—a climate service for Flensburg,Germany. Futures 127, 102691.

Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., 2017. The Shared socio-economic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. 42, 153–168.

Rohat, G., Flacke, J., Dao, H., van Maarseveen, M., 2018. Co-use of existing scenario sets to extend and quantify the shared socio-economic pathways. Clim. Chang. 151 (3–4), 619–636.

Rounsevell, M.D., Metzger, M.J., 2010. Developing qualitative scenario storylines for environmental change assessment. Clim. Chang. 1 (4), 606–619.

Schweizer, V.J., Kurniawan, J.H., 2016. Systematically linking qualitative elements of scenarios across levels, scales, and sectors. Environ. Model Softw. 79, 322–333.

Sultana, H., Ali, N., Iqbal, M.M., Khan, A.M., 2009. Vulnerability and adaptability of wheat production in different climatic zones of Pakistan under climate change scenarios. Clim. Change 94 (1), 123–142.

Tebaldi, C., Debeire, K., Eyring, V., Fischer, E., Fyfe, J., Friedlingstein, P., Knutti, R., Lowe, J., O'Neill, B., Sanderson, B., Van Vuuren, D., 2021. Climate model projections from the scenario model intercomparison project (ScenarioMIP) of CMIP6. Earth Syst. Dyn. 12 (1), 253–293.

Van Ruijven, B.J., Levy, M.A., Agrawal, A., Biermann, F., Birkmann, J., Carter, T.R., Ebi, K.L., Garschagen, M., Jones, B., Jones, R., Kemp-Benedict, E., 2014. Enhancing the relevance of shared socio-economic pathways for climate change impacts, adaptation and vulnerability research. Clim. Chang. 122 (3), 481–494.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., 2011. The representative concentration pathways: an overview. Clim. Chang. 109 (1), 5–31.

Van Vuuren, D.P., Kriegler, E., O'Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mathur, R., Winkler, H., 2014. A new scenario framework for climate change research: scenario matrix architecture. Clim. Chang. 122 (3), 373–386.

Voros, J., 2003. A generic foresight process framework. Foresight 5 (3), 10–21.

Wright, G., Cairns, G., Bradfield, R., 2013. Scenario methodology: new developments in theory and practice: introduction to the special issue. 80 (4), 561–565.

Yu, W., Yang, Y.C., Savitsky, A., Alford, D., Brown, C., Wescoat, J., Debowicz, D., Robinson, S., 2013. Indus basin of Pakistan: impacts of climate risks on water and agriculture. Directions in Development;Countries and Region. World Bank. © World Bank, Washington, DC . https://openknowledge.worldbank.org/handle/10986/13834 License: CC BY 3.0 IGO.

Zhu, T., Ringler, C., Iqbal, M.M., Sulser, T.B., Goheer, M.A., 2013. Climate change impacts and adaptation options for water and food in Pakistan: scenario analysis using an integrated global water and food projections model. Water Int. 38 (5), 651–669.

Zscheischler, J., Westra, S., Van Den Hurk, B.J., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A., Bresch, D.N., Leonard, M., Wahl, T., Zhang, X., 2018. Future climate risk from compound events. Nat. Clim. Chang. 8 (6), 469–477.

Zurek, M.B., Henrichs, T., 2007. Linking scenarios across geographical scales in international environmental assessments. Technol. Forecast. Soc. Chang. 74 (8), 1282–1295.