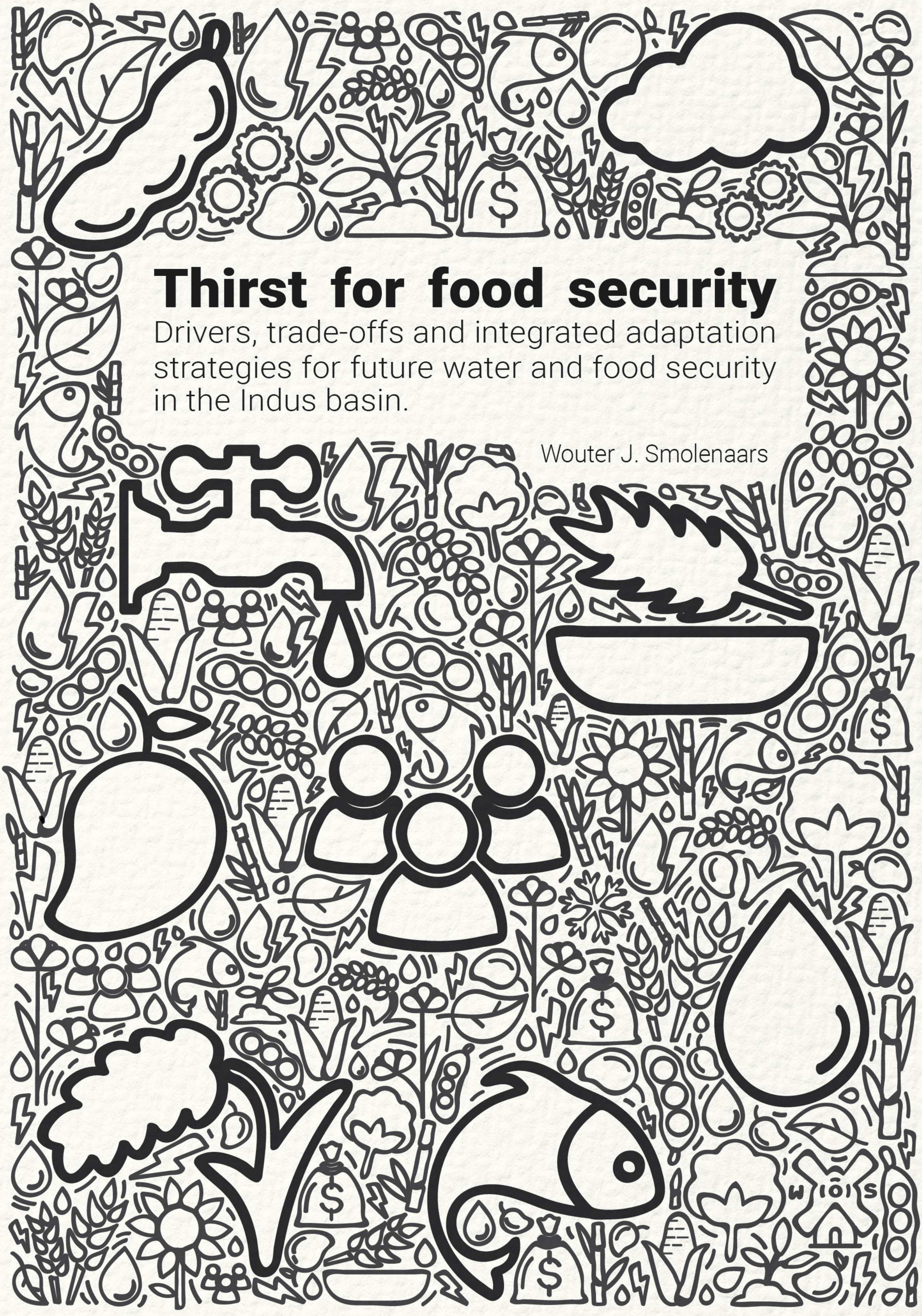
Thirst for food security

Drivers, trade-offs and integrated adaptation strategies for future water and food security in the Indus basin.

Wouter J. Smolenaars



Propositions

1. Food self-sufficiency and sustainable water management are irreconcilable in the Indus basin if the population continuous to grow. (this thesis)
2. In the long run, water security is a more fundamental concern than food security. (this thesis)
3. The outcomes of explorative modelling studies are meaningful only when the link to the assumptions made to obtain them is clear.
4. The societal value of scenario-based adaptation studies has a short expiration date.
5. Teaching and supervising students make for a better PhD experience.
6. The most important skill for doing a PhD is to be pragmatic.

Propositions belonging to the thesis, entitled

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Wouter J. Smolenaars
Wageningen, 29 Augustus 2023

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This research was conducted under the auspices of the Graduate School Socio-Economic and Natural Sciences of the Environment (SENSE)

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Drivers, trade-offs and integrated adaptation strategies
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Wouter J. Smolenaars

Thesis
submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 29 August 2023
at 11 a.m. in the Omnia Auditorium.

Wouter J. Smolenaars
Thirst for food security
Drivers, trade-offs and integrated adaptation strategies for future water and food security in the Indus basin,
161 pages.

PhD thesis, Wageningen University, Wageningen, the Netherlands (2023)
With references, with summary in English

ISBN 978-94-6447-783-2
DOI 10.18174/634160

Abstract

Food production in the densely populated Indus basin depends heavily on irrigation. The high demand for irrigation water causes numerous water scarcity issues and strongly contributes to the basin being one of the most water stressed places in the world. Water and food security in this region are thus highly interdependent, but also negatively affect each other. These trade-offs are expected to intensify under future climatic and socioeconomic changes. To achieve the Sustainable Development Goals (SDGs) for water and food security (SDG2 & SDG6), adaptation strategies are required that balance long-term water management and food production objectives and account for the future impact of climate change. This thesis aims to support adaptation planning in the Indus basin by providing detailed spatial information on drivers, trade-offs and potential integrated adaptation strategies for future water and food security. The results demonstrate principally that socioeconomic changes will rapidly increase the demand for both water and food resources in the future. This will intensify competition for water between agriculture and other water-users, such as the domestic and industrial sector, and between the upstream and downstream. However, meeting the growing food demands under climate change requires irrigated food production to expand and leads to an increase in irrigation water demands. This further intensifies water competition and will therefore strongly exacerbate water scarcity issues. Sustainable limits on irrigation water demand may accommodate these growing water demands of other sectors, but may make food self-sufficiency in the basin unattainable on the long-term. The use of adaptation pathways identified adaptive actions that can combine food production gains with irrigation water savings. Nevertheless, under continued population growth, these mutually beneficial measures are insufficient, and pathways are eventually forced to prioritize either water or food security objectives. This thesis highlights that technical changes to the food production system and associated water management practices are a powerful mechanism for adaptation planning in the Indus basin. However, ensuring robust progress for the SDGs requires modifications to the food production system to be integrated into broader strategies for sustainable development that can address the adverse trade-offs that such changes may cause. Furthermore, this thesis provides important methodological insights and lessons for future modelling studies in other complex river basins with similar strong linkages between water and food security.

Contents

1. General Introduction

Integrated water & food security and the future of the Indus basin

This thesis investigates how relations between water management and food production may develop in the Indus basin and explores integrated strategies that can help achieve the UN Sustainable Development Goals related to water and food security. The following chapter first provides a background of the strong connections between water management and food production. In addition, the chapter describes why understanding these connections is important to achieve sustainable future relations between water and food security. Next, the challenges for water and food security in the Indus basin are highlighted, and the main research objective is introduced. The chapter concludes with an outline of the other chapters in this thesis.

1.1. The vital connections between water and food (security)

The connection between water and food stands at the core of society. Without water, it is not possible to grow crops and meet human dietary requirements. Agriculture is the biggest global consumer of fresh water resources (UN-Water, 2018). Considerable water resources are moreover required to process raw agricultural products into consumable foodstuff. In many regions around of the world, precipitation provides sufficient water resources to grow a variety of crops. However, in arid and semi-arid regions, rainfall alone is often not enough to sustain large-scale agriculture (Boretti & Rosa, 2019). Since ancient times, humans have therefore used irrigation systems to supplement rainwater with surface and groundwater resources. These systems ensure that the timing and location at which water is available is no longer at the unpredictable mercy of the weather, but within the human sphere of control. In some regions, this has led to massive systems of barrages, irrigation canals and inter-basin water transfers that have come to dominate regional hydrology (Hoekstra & Mekonnen, 2012). Irrigation has proven crucial for global food production and therefore food security. However, associated water use practices are not without consequence for water systems. Irrigation often occurs in regions with limited water availability and large irrigation water demands exacerbate scarcity issues. This can result in a range of potential problems, from unmet environmental flows (Jägermeyr et al., 2017), to groundwater overextraction (Richey et al., 2015), water pollution (Strokal et al., 2019), and upstream-downstream conflicts over water allocation (Munia et al., 2018).

These interactions demonstrate that water is not just a prerequisite to cultivate food crops, but that food production also affects water quality and availability. The way in which society pursues food security therefore extensively influences the status of water security, especially in regions with large irrigation systems (Jägermeyr et al., 2016). Similarly, changes in water availability and water management have important consequences for irrigation water supply and therefore for food security (Wada et al., 2013). This complex network of dependencies, cross-sectoral impacts and interactions is known as the water-food nexus. The nexus perspective prescribes that water and food are inherently linked to such a degree through agriculture that they cannot be seen as separate systems, but instead form one interconnected water-food system (Corona-López et al., 2021). Changes to any specific resource are likely to permeate through the system and have consequences for other system elements as well. This means that resource management strategies focused on isolated objectives for a specific sector may hold unintended negative externalities for the security of other sectors. Conversely, integrated management approaches that acknowledge the broader system with its internal interactions can prevent changes that carry the risk of trade-offs, and instead identify actions that capture synergies between sectors and objectives (Cai et al., 2018). To support such holistic approaches, it is important to first understand how water and food security interact and what implications specific management strategies and external developments may have for this interaction (Pahl-Wostl, 2021).

1.2. Sustainable Development Goals and future water and food security

In 2015, the United Nations established the Sustainable Development Goals (SDGs) as a shared global blueprint to promote integrated action for sustainable human and planetary wellbeing (UN, 2015a). The SDGs framework specifically acknowledges the many interdependencies between societal and environmental challenges around the world on the basis of seventeen distinct, yet interconnected, development objectives for the year 2030. Two of the SDGs, namely 'Zero Hunger' (SDG2) and 'Clean Water and Sanitation' (SDG6), directly relate to food and water security. The operational targets associated with SDG2 and SDG6 highlight several important connections between water security and food security objectives, and indirectly link to other SDGs such as 'Responsible Consumption and Production' (SDG12), 'Climate Action' (SDG13) and 'Life on Land' (SDG15). For example, SDG2 emphasizes the need for sustainable food production systems to be more drought resistant and preserve ecosystems. The SDG6 targets likewise call for considerable increases in agricultural water-use efficiency and restrictions on unsustainable water withdrawals. Previous studies have therefore recognized the SDGs as an important framework to appraise interactions between water management and food productions strategies, and as a starting point to develop coherent policies that aim to reconcile water and food security (Rasul, 2016; Weitz et al., 2014; Yillia, 2016). However, the biophysical conditions and societal needs that shape water-food challenges around the world are continuously evolving. This process, known as global change, can alter relations between water and food security and influence the strategies required to achieve the corresponding SDGs (Fuso Nerini et al., 2019).

The most important global driver of changing water-food interactions is climate change. Precipitation patterns worldwide, for instance, are becoming more extreme. Drought events are consequently expected to become more frequent and intense, especially in semi-arid regions (Konapala et al., 2020). This directly affects water security, but can also amplify the dependency of agriculture on irrigation and groundwater resources (Wada et al., 2013). Many places in the world, in particular in the Global South, additionally face ongoing population growth and rapid economic transitions (UN, 2015b). Such socioeconomic developments can cause water demands for domestic and industrial purposes to surge exponentially (Wada et al., 2016) and simultaneously drive substantial increases in food demands and corresponding agricultural water requirements (Bijl et al., 2017). In some regions, the combined impact of climatic and socioeconomic changes will make achieving the SDGs highly challenging (De Souza et al., 2015). Previous studies therefore suggested that the SDGs should go beyond accounting for present-day intersectoral trade-offs, and towards systems approaches that recognize the broader interdependencies between sustainable environmental and societal development, and climate change adaptation (Stafford-Smith et al., 2017; Szabo et al., 2016). This means that strategies in support of SDG2 or SDG6 must integrate other SDGs, but also consider the long-term influence of global change to ensure that progress for water and food security is robust beyond 2030 (Sachs et al., 2019). Given this complexity, quantified insight into the interactions between global change and SDGs is a prerequisite for integrated adaptation planning (Stafford-Smith, 2014; Yillia, 2016).

1.3. Modelling future water and food interactions under global change

An important approach to explore how system states and patterns may develop in the future is to simulate system behavior with the use of computer models. Accordingly, myriad environmental models exist that simulate hydrological, climatological, water allocation and crop growth processes with various levels of integration. Such models range from simple linear regression equations that are based mainly on statistical relations, to fully distributed models that aim to accurately replicate system processes and internal feedback loops (Jajarmizadeh et al., 2012). To this last category of complex models also belong integrated crop-hydrology models, which represent both the physical processes of the water cycle and the influence of environmental factors, such as water availability, on plant development. This type of model is therefore often used to study possible future relations between hydrology, food production and global change (Siad et al., 2019). The interactions and dependencies between agriculture and hydrology span large geographical areas and are frequently characterized by strong differences between seasons. Many crop-hydrology models therefore have an explicit spatial dimension and simulate processes at frequent interannual timesteps. Model outcomes are thus able to illustrate not just the direction in which water-food interactions may develop, but may also identify the locations and times at which such changes occur. This type of detailed information on potential system changes, for whichever driver is of interest, supports adaptation planning in the context of SDGs for water and food security with identifying future priorities and concerns (Siad et al., 2019; Taylor et al., 2013).

Hydrological and crop-hydrology models are frequently applied to assess how climate change may affect the global hydrological cycle (Konapala et al., 2020; Tapley et al., 2019; Wanders et al., 2015; Wu et al., 2020). These biophysical changes are often connected to societal implications by determining potential consequences for water availability and global water stress (Gosling & Arnell, 2016; Koutroulis et al., 2019; Pokhrel et al., 2021). In doing so, some modelling studies additionally account for socioeconomic developments. Such changes are however included mostly to enhance indicators of climate change impacts (e.g. accounting for population growth when quantifying the inhabitants of vulnerable areas), rather than as autonomous drivers of system change that also influence water demands and hydrology. Global assessments of food production under climate change similarly determine implications for food security and water demands (Jägermeyr et al., 2021; Leng et al., 2015; Malek et al., 2018), but few quantitatively link this to changing food demands or water security interests. Those studies that do explicitly investigate global interactions between future food needs and sustainable water management under global change largely focus on specific segments of this relation, such as global trade-flows (Pastor et al., 2019), water allocation (Bijl et al., 2018) or planetary boundaries (Gerten et al., 2020; Jägermeyr et al., 2016). Global level modelling efforts therefore hold important information to identify 'hotspot' regions for future water-food challenges, but do not fully disentangle how the interlinkages between water and food security develop in these regions (McNeill et al., 2017).

However, adaptation planning in support of water and food security occurs predominantly at local and regional scales (Cremades et al., 2019). Modelling outcomes that do capture more detailed regional water-food dynamics are therefore also needed, especially for aforementioned hotspot regions. Further integration by quantitative global approaches is limited primarily due to the vast complexity and uncertainty associated with water-food-climate interactions (Hibbard & Janetos, 2013). Integrated models cannot account for all possible cross-sectoral feedbacks and trade-offs, and must therefore simplify and abstract system processes to allow the dynamics that are of interest to be studied. For global studies, such methodological choices are often geared towards universal global relevance and subsequent outputs therefore remain relatively general. Regional modelling approaches, however, are less bound by likewise constraints as these focus on representing only the water-food dynamics that govern a particular regional setting. Studies with a regional scope can therefore include more detail and specificity in model-design, allowing for deeper integration, and thus for more complex interactions to be investigated (Vinca et al., 2021). Explorative modelling studies moreover rely on scenarios and corresponding assumptions to gather input data on potential future developments. Regionalized approaches allow for scenarios to be tailored to the regional context, for instance through co-creation with policymakers, and emphasize changes that dominate the adaptation discourse (Hibbard & Janetos, 2013). Regional integrated modelling is therefore a vital tool to assess relations between water and food security, SDGs and drivers at a scale that is appropriate for adaptation planning (Cremades et al., 2019).

1.4. The Indus basin: a hotspot for trade-offs between water and food security

One region that is consistently highlighted by global studies as a hotspot for trade-offs between water and food security is the Indus basin (Immerzeel et al., 2020; Jägermeyr et al., 2017). Shared between Pakistan, India, Afghanistan and China, the basin is home to over 270 million people. Most inhabitants are concentrated on the fertile, but arid to semi-arid, plains (see Figure 1.1B) of the lower Indus basin. The densely populated Indus plains have less than 1000 m^3 of water available per capita and are one of the most water stressed places on earth (Junguo Liu et al., 2017). The climatological conditions here also entail that producing sufficient food depends strongly on irrigation. The water requirements of the expansive irrigation systems of the lower Indus account for over 90% of the entire basin's water use (Wijngaard et al., 2018). This system is largely sustained by surface water originating upstream, in the mountains of the upper Indus (Laghari et al., 2012). Water supply from the upper to the lower Indus is however characterized by strong seasonal differences. During the dry season, massive irrigation water demands in the lower Indus by far exceed upstream inflows and leave surface water resources structurally depleted. This results in damage to riverine ecosystems (Basharat, 2019) and drives the unsustainable exploitation of groundwater as a supplementary source of irrigation water (Biemans et al., 2019b). Despite the severe problems that food production already causes for water security in the Indus basin, regional food security remains precarious (Rasul, 2016).

Further pressure on either food production or the division of water resources in the Indus basin is likely to have negative implications for both food and water security (Wada et al., 2019). South Asia is currently also facing rapid population growth and the Indus basin population is projected to double, or even triple, in the coming decades (Samir & Lutz, 2017). The economies of some riparian states are additionally among the fastest developing in the world (Dellink et al., 2017). This will probably affect dietary preferences and increase household food consumption (Bijl et al., 2017). The food production system of the Indus basin will therefore need to accommodate a rapidly expanding population that gradually demands more food per capita. This is likely to put further strains on the adequacy of irrigation water supply. Simultaneously, however, the economic transition in the basin places a fast expanding claim on water resources for industrial and manufacturing purposes (Bijl et al., 2016). Population growth and rapid urbanization similarly cause domestic water requirements in urban areas of the basin to grow exponentially (Flörke et al., 2018). These developments are accompanied by an increasing energy demand, which depends heavily on water too, for example by exploiting the hydropower potential of the upper Indus (Rasul, 2016). Socioeconomic changes thus increase food demand in the Indus basin, but are also likely to increase competition for water between the irrigation demands of the agricultural sector, and the needs of other sectors.

The large distances between origin and consumption of water resources in the basin additionally mean any sectoral division of water is subject to upstream-downstream dependencies, many of which are transboundary. Intensifying competition over water resources may affect downstream water availability and thus escalate the already tense hydropolitical relations (Qamar et al., 2019). Climate change will similarly influence the timing and location of water availability throughout the Indus basin. While future precipitation patterns are highly uncertain, total annual discharges in the upper Indus are consistently projected to increase, largely due to accelerated glacial melt associated with increased temperatures (Wijngaard et al., 2017). This will however be accompanied by an intensification of hydrological extremes. Discharges in the upper Indus are projected to surge especially during the monsoon season when downstream water availability is already abundant, amplifying the propensity for destructive flood events, while discharges during the dry season may further decrease (Dahri et al., 2021). Climate change is thus likely to make the timely supply of vital surface water resources from the upper Indus for irrigation downstream less dependable. This may compound the pressure exerted by socioeconomic changes on transboundary water allocation here and increase agricultural groundwater dependency (Lutz et al., 2022; Qamar et al., 2019). Climate change will moreover increase heat stress and induce severe production losses for irrigated agriculture on the Indus plains (Droppers et al., 2022). Previous studies subsequently designated the Indus basin as a 'climate change hotspot' (De Souza et al., 2015; Immerzeel & Bierkens, 2012; Kilroy, 2015).

1.5. Integrated adaptation to support the SDGs in the Indus basin

The relation between the water system and the food production system of the Indus basin is unsustainable and subsequently inflicts significant negative trade-offs for both water and food security. This, in combination with the further pressure exerted by beforementioned socioeconomic and climatic changes, means that achieving the interlinked SDGs for water and food security (SDG2 and SDG6) here is highly challenging. Central to this predicament is the food production system and the massive corresponding irrigation water demands. Foremost, the severe water stress already experienced in the basin results in many water scarcity issues and necessitates urgent action. These problems are mainly caused by high water demands, almost exclusively for agriculture, structurally exceeding what the basin can sustainably provide for a large part of the year (Wada et al., 2019). Water management changes aimed at improving water security will therefore likely entail modifications, or limitations, to the supply of irrigation water. This is especially crucial if water resources must increasingly be made available for domestic and industrial purposes too. Yet, safeguarding future food security will require regional food production to increase considerably and compensate for gradually more hostile climatic conditions. With the current food production system, this will be very difficult without additional water resources for irrigation, let alone a decrease in water supply. Previous studies therefore suggested that to achieve the SDGs, food production in the Indus basin must adapt to produce more food with less irrigation water (Janjua et al., 2021; Qureshi & Ashraf, 2019; Rasul, 2016).

Adaptation strategies that pursue integrated sustainable water management and food security objectives are therefore urgently required in the Indus basin. The strong linkages between water stress, irrigation water demands and food production mean that such strategies must focus primarily on balancing the relation between water management and the food production system in support of SDG2 and SDG6. Nonetheless, any potential changes aimed at water and food security should also consider effects and synergies with other interlinked SDGs, such as energy security (SDG7), ecosystem health (SDG15) and long-term climate resilience (SDG13). The complexity of these interdependencies between SDGs in relation to highly uncertain climatic and socioeconomic changes makes defining robust adaptation trajectories challenging. Adaptation planning in the Indus basin must therefore be informed with detailed and context-specific information on how and where current water-food dynamics affect the SDGs, and on the long-term implications of particular drivers and adaptive actions (Biemans & Siderius, 2019; Yillia, 2016). Several regionalized assessments accordingly quantified trade-offs between water availability and agriculture (Biemans et al., 2019b; Droppers et al., 2022;

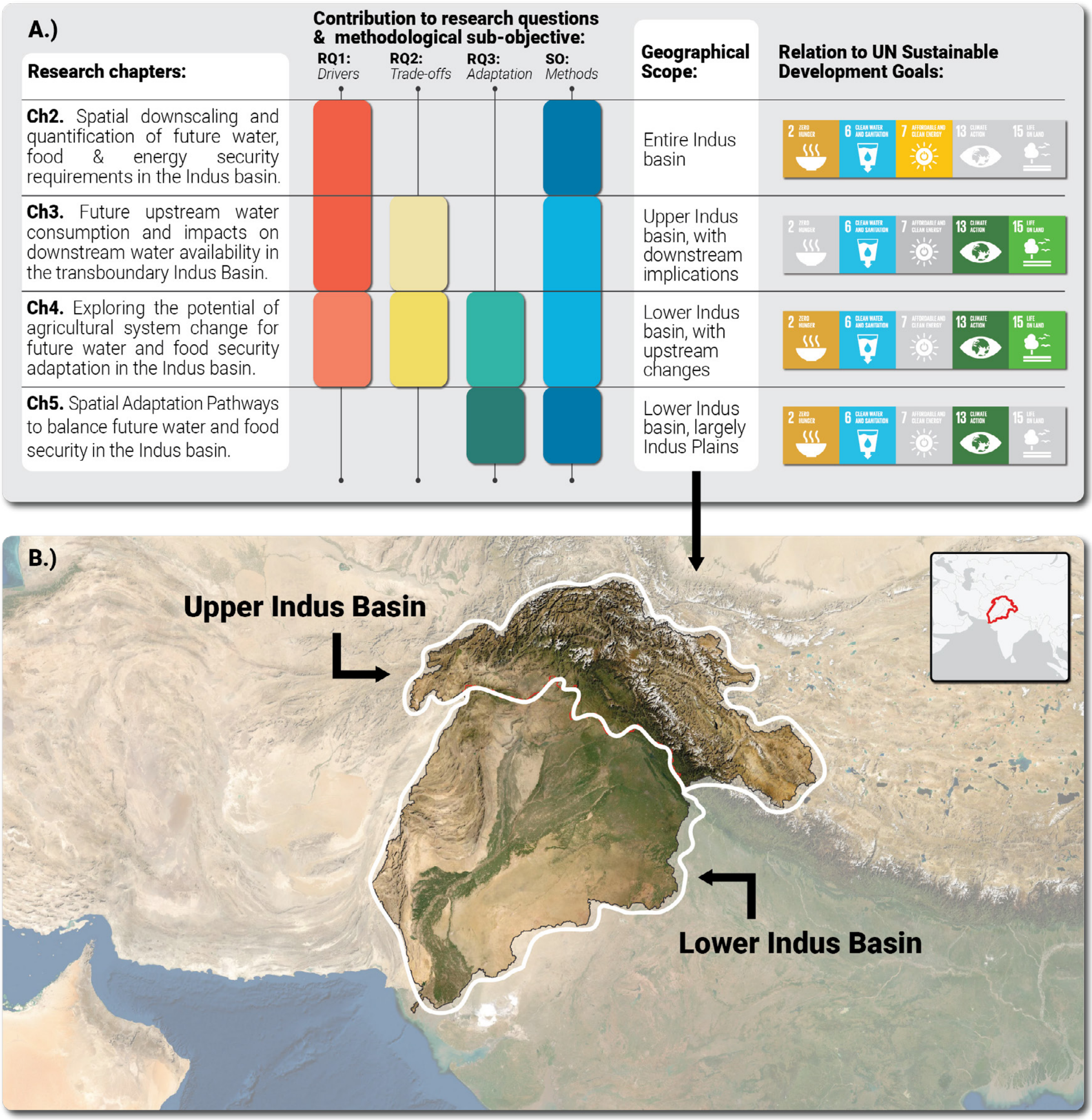


Figure 1.1: Overview of the contribution of each research chapters (top panel) to the three research questions that together address the main research objective, and to the methodological advancements that are addressed in the overarching sub-objective. The darker coloured bars indicate a major contribution and the lighter coloured bars a minor contribution. In addition, the geographical scope of each research chapter, and the relation to the SDGs targeted in this thesis is indicated. The SDGs that are greyed out are not addressed in that particular research chapter. The bottom panel shows the geographical location of the Indus basin and the delineation of the lower and upper Indus basin used in this thesis.

Kirby et al., 2017), and for the water-food-energy nexus (Momblanch et al., 2019; Siderius et al., 2022; Yang et al., 2016), but none fully accounted for the influence of both climatic and socioeconomic changes. Regional studies that did explicitly account for both drivers either excluded adaptation (Lutz et al., 2022; Wijngaard et al., 2018), or focused on the econometric optimization of SDG investments, rather than direct interactions between objectives for water and food security (Vinca et al., 2020).

1.6. Research objectives: data to support Indus basin adaptation planning

Overall, the individual links between sustainable water management, food production, climate change and socioeconomic development in the Indus basin are relatively well understood, and illustrate that enormous challenges await for achieving the SDGs associated with water and food security here in the coming decades. However, holistic and quantified knowledge on how all these combined factors together interact to shape future trade-offs and dependencies between the strongly interconnected water and food production systems remains limited. This constrains the comprehensive evaluation of synergetic adaptation strategies and is thus a major obstacle for robust and integrated adaptation planning to support SDG2 and SDG6 on the long-term. It is therefore both scientifically and societally important to examine the suitability of potential adaptation strategies for integrated water and food security in the Indus basin on the basis of a thorough system analysis, and with a modelling approach that represents the unique regional processes and characteristics that define the adaptation context here. The main research objective of this thesis is hence as follows:

- *To quantitatively explore how water management and food production in the Indus basin can be adapted to support both water and food security related Sustainable Development Goals in the face of climatic and socioeconomic changes.*

The main research objective is addressed by three successive research steps (see Figure 1.1A) that each focused on simulating different types of interactions and dependencies between water and food security. The first research step systematically disaggregated how specific regional **drivers** may affect the relation between the water system and the food production system of the Indus basin on the short-term (i.e. 2030) and long-term. This step focused especially on the distinctive socioeconomic factors, such as strong transboundary upstream-downstream linkages, that adaptation planning in the Indus basin must account for, as these have so far received less scientific attention than regional climatic trends (Biemans & Siderius, 2019). The second research step quantified the effect that these regional drivers, and potential adaptive actions in response to them, may have on **trade-offs** between water and food security. This knowledge was then used in the third research step to develop synergetic **adaptation** strategies for integrated water and food security in the basin and evaluate the degree to which these strategies are able to support achieving the corresponding SDGs (SDG2 and SDG6) on the long-term, in relation to the pressure exerted by the regional drivers. In addition to SDG2 and SDG6, the research steps also varyingly account for the relations of water and food security changes to other SDGs (see Figure 1.1A). Each research step is accompanied by a research question that is targeted in a combination of research chapters:

1. *How do socioeconomic and climatic drivers affect supply of and demand for water and food? (Identify drivers: Chapters 2, 3 and 4);*
2. *How may trade-offs between water and food security develop on the long-term? (Define trade-offs: Chapters 3 and 4);*

3. *To what extent can adaptation of the food production system support SDGs for water and food security on the long-term? (Evaluate adaptation strategies: Chapters 4 and 5).*

For each research step, particular consideration was given to ensure that the modelling approach is representative of the water-food dynamics and adaptation challenges of the Indus basin. In addition, the explorative nature of this thesis required the complex interactions between the water and food production system to be assessed from many different perspectives. This combination demanded considerable methodological development during the research steps, either by the adjustment of existing modelling tools and datasets to the Indus basin setting, or by designing entirely new quantitative approaches. Both the newly developed tools themselves and the novel approaches used to downscale and regionalize existing tools may provide important conceptual and general methodological insights for similar future research in other regions that experience strong interlinkages between the water and food production systems. This thesis therefore has an additional methodological sub-objective that goes beyond the scope of the Indus basin and aims to contribute general scientific knowledge:

- *To draw methodological lessons for quantitative assessments in support of the Sustainable Development Goals in regions with strong water-food interactions.*

This overarching sub-objective is addressed by a thorough reflection on the methodological advancements of the three research steps in the last chapter (Chapter 6) of this thesis.

1.7. Research approach and thesis outline

The research approach used in the three research steps revolves largely around two methods; integrated regional modelling and scenario building (see Figure 1.2). Foremost, interactions between the water and food production systems of the Indus basin were quantified using the fully distributed *Lund-Potsdam-Jena managed Land* (LPJmL) crop-hydrology model (Bondeau et al., 2007). The LPJmL model dynamically simulates both hydrology and plant growth at daily timesteps, and therefore allows feedbacks between water availability, irrigation demands and food production to be determined through space and time (Gerten et al., 2011). The LPJmL model used in this thesis is an adjusted version by Biemans et al. (2019b) at 5x5 arcmin resolution that accounts for double-cropping, the operation of irrigation systems and the effect of large reservoirs. This model version is therefore highly suited to study water-food-climate interactions on the irrigation-dependent plains of the Indus basin (Lutz et al., 2022; Wijngaard et al., 2018). Secondly, to manage and understand the large uncertainties surrounding socioeconomic and climatic changes, regional scenarios for the Indus basin were developed. These scenarios are internally consistent sets of assumptions about different possible futures (Rounsevell & Metzger, 2010), and were designed over the course of the research steps to emphasize specific regional developments that are relevant for adaptation planning in the basin. Various scenario elements were therefore defined and validated in cooperation with regional stakeholders and experts. The scenarios were quantified and spatialized to serve as input data for simulations with the LPJmL model or as indicators to assess model outputs.

The research steps addressed the research questions through four scientific articles (see Figure 1.1A), presented in research chapters two to five, as follows:

1. **Identify drivers:** in first research step, global socioeconomic development scenarios were regionalized for the Indus basin, spatially downscaled, and coupled to preexisting

regional climate change projections to form a base set of regional integrated scenarios (Chapter 2). The scenarios were used to determine the isolated and combined impacts of regional drivers on future security demands for water, food and energy related SDGs (Chapter 2), and on future per capita water availability (Chapter 3), throughout the Indus basin. In addition, plausible agricultural development trajectories were defined, discussed with stakeholders and policy makers, and embedded in the regional scenarios as an independent driver of system change (Chapter 4). The influence of different agricultural development directions on potential future food production and corresponding agricultural water demands were then quantified under climate change with the LPJmL model.

2. **Define trade-offs:** the second research step used the regional scenarios to quantify future water consumption in the upper Indus in relation to availability under climate change, and determined the ensuing consequences for water supply to the lower Indus (Chapter 3). The future trade-offs between increasing upstream water needs and downstream water stress were then assessed to establish implications for future transboundary upstream-downstream linkages in the basin. Similarly, the LPJmL model was forced with the agricultural development trajectories and encompassing scenarios to simulate future trade-offs between producing sufficient food for the basin in the face of population growth and climate change, and mitigating water stress (Chapter 4). Spatial projections of future domestic and industrial water withdrawals were developed on the basis of the regional scenarios and accounted for in the LPJmL simulations. The potential impact of growing demands in other sectors on competition for irrigation water resources, and therefore on water stress throughout the basin, were accordingly established.
3. **Evaluate adaptation strategies:** for the third research step, the agricultural development trajectories were further evaluated in the context of water and food security related SDGs to define general advantages and drawbacks for integrated adaptation (Chapter 4). The corresponding LPJmL modelling outputs were in addition spatially disaggregated to identify specific locations and instances were agricultural changes are sustainable on the long-term, or even mutual beneficial, for both objectives. These location-specific changes were used alongside technical interventions as adaptation options in the construction of spatial adaptation pathways for sustainable irrigated wheat production in the lower Indus (Chapter 5). To do so, a novel pathways tool was designed that specifically represents spatial water-food dependencies for adaptation of the food production system. The potential of the pathways as integrated adaptation strategies was evaluated by testing their performance against multiple indicators of SDGs for water and food security (SDG2 and SDG6), under the pressure exerted by the regional scenarios drivers.

Lastly, in Chapter 6, the outcomes of the research steps are synthesized with regards to the main research objective and discussed in a broader context. In addition, the uncertainties, limitations and novelties of the research approach are examined to address the additional methodological research question. The chapter concludes with the main findings for adaptation planning in the Indus basin and an outlook for future research.

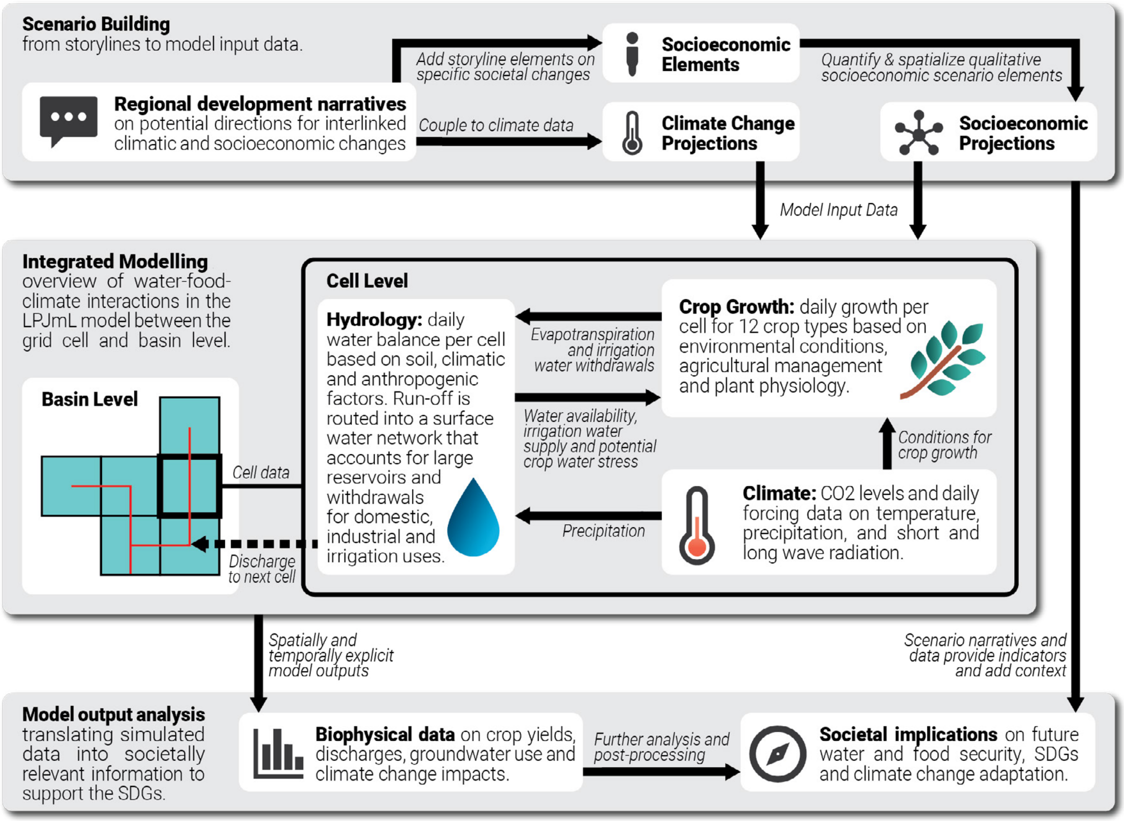


Figure 1.2: Conceptual overview of the linkages between scenario building and the integrated modelling approach of this thesis, revolving around the LPJmL model (central panel). The schematical overview of water-food-climate interactions by the LPJmL is based on the model version by Biemans et al. (2019b). The LPJmL simulates both plant growth and the water balance with daily timesteps at the cell level (represented by the 'crop growth' and 'hydrology' components, respectively), whilst accounting for numerous interactions between these two aspects. The model processes are forced with daily climate data (represented by the 'climate' component).Water influxes for each cell foremost come from precipitation. Part of this water becomes run-off to the surface water and another part infiltrates through five soil layers to ultimately become groundwater. Water can in addition leave a cell through evapotranspiration from crops and natural vegetation. Changes in the type of crops that are grown in a cell, or changes in the crop water requirements due to climatological or management changes, can thus influence the water balance. Similarly, the crop growth module accounts for environmental conditions, such as the climate and the availability of water. If there is insufficient water available in a cell, crops may suffer water stress, which can limit growth. For cells that are equipped for irrigation, water inputs can also come from the application of irrigation water. Irrigation water is sourced from surface water, reservoirs and, in last case, the groundwater. Water from these sources is similarly extracted for domestic and industrial purposes, which take priority over irrigation demands. The cells are spatially connected to each other through the surface water which is routed in a river system. This means that surface water availability for human uses, such as irrigation, also depends on inflows from upstream cells. Changes that affect the run-off or extract surface water in upstream cells can therefore affect the surface water available to downstream cells. This means that the LPJmL model is also able to simulate the upstream-downstream consequences that discharge changes due to human water-use and climate change may induce.

2. From Narratives to Numbers

Spatial downscaling and quantification of future water, food & energy security requirements in the Indus basin

The Indus basin features severe water stress, and the combination of climate change and rapid socio-economic development will further increase the pressure on water, food and energy resources. Integrated adaptation strategies are needed to achieve the highly interlinked Sustainable Development Goals (SDGs) for water, food and energy security in the basin. However, detailed quantitative scenarios for the plausible dimensions of future resource security requirements under socio-economic development are lacking. Here we define three quantitative and spatially downscaled scenarios for future water, food and energy requirements in the Indus basin and we assess the implications of socio-economic development for the integrated resource security challenge. High-resolution gridded scenarios for resource security requirements are developed by combining three regionalized and spatialized Shared Socioeconomic Pathways (SSPs) with quantitative regional water, food and energy security thresholds. The results demonstrate that by 2080 basin level water and energy security requirements are likely to at least double and potentially triple compared to the current situation. Food requirements could increase only marginally and double at most. Migration and urbanization additionally drive the growing requirements to spatially converge around the largest cities of the basin on the Indus plains and at the foothills of the high Asian mountain ranges. This demonstrates that socio-economic development increases the complexity of the water-food-energy security challenge by increasing its magnitude and spatial concentration. Future research and policymaking should anticipate for the heterogeneous growth of resource security challenges when developing adaptation strategies.

Published as: Smolenaars, W.J., Lutz, A.F., Dhaubanjar, S., Immerzeel, W.W., Biemans, H., Ludwig, F. (2021). "From narratives to numbers: Spatial downscaling and quantification of future water, food & energy security requirements in the Indus basin." Futures, 133, 102831.

2.1. Introduction

The transboundary Indus basin is one of the most vulnerable areas in the world (De Souza et al., 2015; Immerzeel et al., 2020). The basin is shared by Pakistan, India, Afghanistan and China, causing considerable hydro-political tensions (Laghari et al., 2012). The densely populated lowlands of the Indus basin are arid and largely depend on melt water coming from the upstream mountainous areas for its societal and economic functioning (Biemans et al., 2019a; Wijngaard et al., 2018). The bulk of water resources is allocated to sustain one of the largest irrigation system in the world (Wijngaard et al., 2018), while water is also required for hydropower, on which the regional energy production depends considerably (Molden et al., 2014). The multi-sectoral water demand has pushed the system beyond its biophysical limits. The Indus basin is among the most water stressed in the world, relying significantly on the unsustainable over-extraction of groundwater (Richey et al., 2015; Wanders et al., 2015), while water, food and energy security requirements in the basin are currently not being met (Molden et al., 2014; Rasul, 2014; Yang et al., 2016).

Climate change also alters the water supply of the basin and affects the viability of food and energy production (Lutz, Immerzeel, et al., 2016; Lutz et al., 2019). Moreover, the Indus basin is projected to face rapid socio-economic development (UN, 2015b). The growth in population and economic development will exponentially increase societal demand for water, food and energy resources (Rasul, 2016; Wijngaard et al., 2018). Satisfying these demands will put additional stress on the already limited water resources (Yang et al., 2016). The combination of a precarious present-day situation with rapidly diverging gap between water resource supply and demand, makes achieving and maintaining the water security *Sustainable Development Goal* (SDG 6) in the Indus basin extremely challenging. Given their water-dependency, the food and energy security SDGs (2 & 7, respectively) are also at risk (Rasul, 2014, 2016). Integrated adaptation efforts that simultaneously ensure water, food and energy security are therefore essential (Immerzeel et al., 2020; Rasul, 2014).

To develop adaptation strategies that fit the complex water-food-energy security challenge of the Indus basin, it is critical to have a quantitative understanding of the magnitude and range of the future adaptation deficit (Chang et al., 2016). However, the SDGs are defined at the global scale in a universal, qualitative manner. Its indicators, and their interaction with socio-economic development, need to be quantified respective of the regional context to become actionable security targets (Weitz et al., 2014; Yillia, 2016). Given the dominant role of socio-economic changes in the vulnerability of the Indus basin (Immerzeel et al., 2020; Momblanch et al., 2019; Wijngaard et al., 2018), this requires a clear operationalisation of water, food and energy security thresholds, and insight into how associated resource requirements within the basin may develop over time under socio-economic development (Weitz et al., 2014; Yillia, 2016). Such information must be available at disaggregated sub-national levels to be of direct use in adaptation policy making (Rasul, 2014; Weitz et al., 2014).

Considerable advances have been made in understanding the hydrological and climatological processes of South-Asian river basin. Regional water-food-energy nexus modelling studies (Momblanch et al., 2019; Wada et al., 2019; Wijngaard et al., 2018) have however predominantly relied on exerts from global studies to represent the future socio-economic context and assess its interaction with the hydrological system (Biemans & Siderius, 2019). Despite several qualitative assessment of regional nexus security challenges (Rasul, 2014, 2016), quantifications of future water-, food-, and energy security requirements in the Indus basin remain largely derived from global studies (Bauer et al., 2017; Falkenmark et al., 2009; Gain et al., 2016).

However, these quantifications have been established at coarse country, basin or even macro-region scales using universal water, food and energy security thresholds. The socio-economic development context in these studies is sourced from the basic global narratives of the global *Shared Socio-economic Pathways* (SSP) framework (Riahi et al., 2017). Key socio-economic variables that drive the resource security challenge in the Indus basin, such as population growth and urbanisation patterns (Rasul, 2016), follow global assumptions and ignore the Indus basin's heterogenous policy- and socio-economic context. Another complication is that the projected resource requirements are often spatially allocated to current population distributions. Regional future urbanisation- and migration trends are not accounted for in global projections, while these are key drivers that affect both the magnitude and spatial distribution of domestic water, food and energy security requirements in the Indus basin (Chang et al., 2016; Rasul, 2016; Roy et al., 2019; Siddiqui et al., 2019). Spatially explicit socio-economic scenarios that are tailored to the context of the Indus basin are therefore needed to understand future nexus security challenges, as a benchmark for assessing the SDGs and to formulate and evaluate adaptation policies.

In the absence of spatially detailed scenarios, existing assessments do not capture the dynamic resource security context of the Indus basin. They provide little understanding of the heterogeneity of future water, food and energy security requirements at the critical local level, where socio-economic upstream-downstream conflicts and trade-offs in resource allocation can arise. The objective of this study is to provide quantitative, downscaled and spatially explicit regional scenarios that constrain the potential ranges of future water, food and energy security requirements in the Indus basin. Furthermore, we aim to assess the implications of socio-economic development for the integrated water-food-energy security challenge of the basin from a nexus perspective.

Our approach combines scenario building with a top-down modelling approach. First, we develop regionalised socio-economic scenarios by extending three basic global SSPs with specific regional development narratives. The scenarios are then spatialised by BasinPop, a population distribution model that was designed specifically to simulate regional urbanisation- and migration processes. Gridded scenarios of future population distributions in the Indus basin are combined with regionally defined per-capita water, food, and energy security thresholds to create spatially explicit scenarios of future security requirements in the Indus basin. Finally, we reflect on the implications of our findings from a water-food-energy nexus perspective and discuss the role these findings play as a benchmark for developing local Indus basin Development Goals.

2.2. Materials and Methods

2.2.1. Population distribution model (BasinPop model)

Several studies have spatialised global population projections using the SSP framework (Jones & O'Neill, 2016; Murakami & Yamagata, 2019; van Huijstee et al., 2018). However, the models used to develop these projections have been designed for the global scale. To spatialise our regional scenarios we have therefore developed *BasinPop*, a population distribution model that was designed to simulate the unique regional context of migration and urbanisation in the Indus basin.

The BasinPop model builds upon the methodological approach used in the global population distribution models HYDE (Klein Goldewijk et al., 2011) and 2UP (van Huijstee et al., 2018). Expansion of urban area and distribution of population both occur based on suitability mapping using weighted layers of explanatory variables, within the constraints of boundary conditions. BasinPop adds five normalized spatial layers of explanatory variables *(distance to urban area*, *distance to major city*, *distance to road network*, *highland-to-lowland* and *terrain suitability*) and three spatial layers of boundary conditions (*border zone*, *current urban area* and *terrain suitability*) to create a suitability map. The distribution procedure additionally uses four socio-economic indicators as input data (*total population, urbanisation fraction, maximum urban density* and *mean urban density).*

The spatial layers that form the basis for the suitability mapping have been selected to mirror historical migration and urbanisation patterns in the region and to account for projected future patterns. This is most evident in the explicit differentiation between the *distance to general urban areas* and the *distance to major cities* as separate explanatory variables. Urbanisation in the wider South-Asia region has historically concentrated at far higher rates towards dense megacities than elsewhere in the world (Cox, 2012; Ellis & Roberts, 2015; Mustafa & Sawas, 2013). The major city variable hence opens the possibility, if a scenario calls for this, of shifting the gravity of urban expansion towards the areas surrounding major population centres. Additionally, the wider Hindu-Kush Himalaya region faces a strong migratory pattern from the highlands to the economically stronger lowlands (Siddiqui et al., 2019; Tiwari & Joshi, 2015). The *highland-to-lowland* layer was developed based on the altitude of sub-regional administrative units to account for this trend in the suitability map. Lastly, the complex geopolitical situation of the Indus basin has considerably affected the development and urbanisation of areas in the vicinity of international borders (Bala & Krishan, 1982; Kannan, 2015). To reflect this the *border zones* boundary condition was added which reduces the suitability of areas close to international borders.

The other explanatory variables, *terrain suitability* and *distance to road network*, are generic explanatory variables also used in other models (Klein Goldewijk et al., 2011; van Huijstee et al., 2018). The *terrain suitability* layer also figures as a boundary condition, providing the biophysical limits to population expansion. Lastly, *current urban area* has been added as a boundary condition to spatially define the current urban extent and dynamically consider the geographical location of pre-existing urban areas in future timesteps. Detailed information on the characteristics and development of the explanatory variables and boundary conditions can be found in Appendix Table A3.

The BasinPop model runs on a 5 arcmin resolution and simulates spatial population density development between two timesteps of any given length on a per-country and -scenario basis using the following algorithm for every simulation run:

- First, for each country basin level external population- and urbanisation development numbers are read to determine the change in total urban- and rural population in the timestep. The future population totals are combined with projected changes in mean urban population density to assess the required change in urban area.
- Next, a gridded suitability map is created by aggregating the explanatory variable layers with a scenario-specific weighting to indicate the suitability of each cell to become urbanized. The suitability of areas that fall within the border zone are corrected by the factor belonging to the relevant scenario.

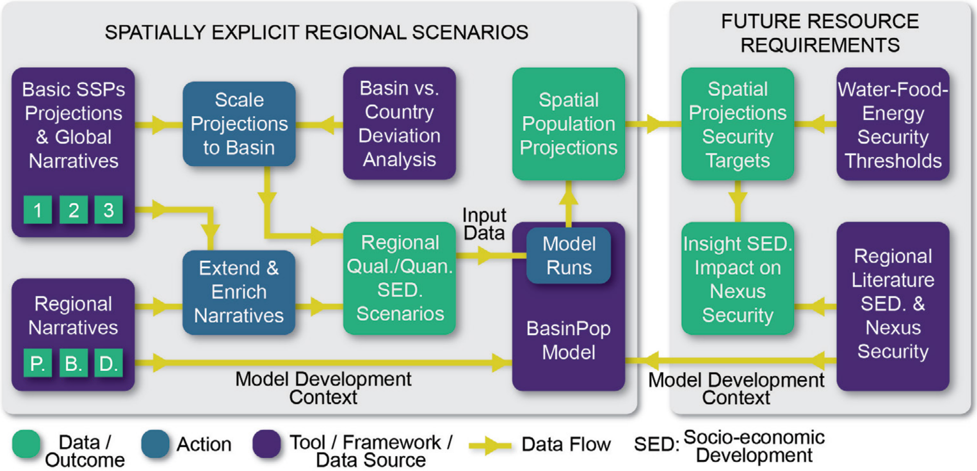


Figure 2.1: Overview of methodological approaches, interlinkages between research steps, and outcomes.

- If the urban area is projected to grow, the required additional urban area is allocated iteratively by converting rural grid cell with the highest suitability until the total required urban area is met. The allocation of new urban area takes the available space for urban expansion into consideration by using the suitable terrain factor.
- Finally, the change in urban and rural population is distributed separately over the urban- and rural areas. The change in population of each grid cell is based on the suitability map. If the total urban or rural population is projected to grow, the most suitable grid cells obtain the largest population increases. A shrinking population leads to the highest population reduction in the least suitable cells. The urban population allocation procedure first allocates over the newly urbanised areas before allocating over the entire urban area. The terrain suitability factor and a scenario-specific maximum population density factor are used to ensure that population totals within cells do not exceed allowable limits.
- For the next timestep, the *current urban area* layer is updated with the newly urbanized areas and the explanatory variable layers are updated. The final population density map forms the new starting point for the next iteration.

We have developed the BasinPop model to be flexible and dynamic so it may be used to project a wide range of plausible futures. In contrast to the relatively static suitability maps in the 2UP and HYDE models, our suitability mapping procedure dynamically recalculates the values of the explanatory variable layers for every simulation based on the relevant socio-economic context and the outcomes of the previous timesteps. Similarly, weightings of explanatory variables and the values of boundary conditions can be easily adapted and may vary for each scenario. This allows us to adhere to distinct urbanisation trends outlined in regionalized socio-economic scenarios. We furthermore allocate population dynamically for both urban and rural areas, using the suitability map to simulate which rural areas are more likely to face population change.

Calibration

Gridded historical timeseries of population distributions for the Indus basin are scarce and existing global datasets, such as HYDE (Klein Goldewijk et al., 2011), have generally based historical population distributions for the region on a static contemporary suitability map. Therefore, we calibrated the BasinPop model with census data at district level for Pakistan over the period 1998-2017, and India for the period 2001-2011. Census data was spatialised using sub-national shapefiles of the Global Administrative Areas dataset (Hijmans, 2015). For Afghanistan, no census data could be obtained, and the Chinese share of the basin was determined to be too scarcely populated for calibration purposes.

We corrected the gridded population distributions of the HYDE dataset for 2000 to respective populations at districts level in 1998 and 2001 for both countries. Gridded population layers were used as the basis for separate model runs for both countries over the respective census periods. We used census data for 2017 and 2011, and urban density data estimations of Cox (2015) as socio-economic input data. Simulated gridded population projections were then aggregated using the district shapefiles and compared to census data. The best combination of explanatory variable weightings was identified to approximate the observed population development per district in both countries using non-linear least squares regression. The weighting was assumed to be consistent across all four riparian states.

2.2.2. Developing spatially explicit regional socio-economic scenarios

Previous integrated modelling studies for the Indus basin and global assessments of future water-food-energy requirements based their scenario context on the *Shared Socio-economic Pathways* (SSP) framework (O'Neill et al., 2014). To maintain consistency with previous studies and benefit from pre-existing datasets, the core of our regional socio-economic scenarios builds onto the SSP framework. The framework offers several '*basic SSPs*' that consist of qualitative global socio-economic development narratives and quantitative projections of main socio-economic indicators (O'Neill et al., 2017). A key step in applying the SSP framework in regional impact assessments is to extend the basic SSPs towards more elaborate scenarios that fit the research objectives and regional context (Absar & Preston, 2015; O'Neill et al., 2017).

We used a three-step approach that integrates quantitative, qualitative and spatial elements to extend the basic SSPs towards spatially explicit regional scenarios required by the scope of our research (see Figure 2.1). To encompass large bandwidth in plausible socio-economic futures the contrasting SSP1 (optimistic, low challenges) and SSP3 (pessimistic, high challenges) narratives were selected as the starting points for the regional scenario development (O'Neill et al., 2017). Additionally, the 'middle of the road' narrative SSP2 was selected, as this moderate scenario may be more suitable for policy making.

Qualitative extension & enrichment of basic SSPs

Qualitative future storylines were developed for the wider Hindu Kush Himalaya (HKH) region during several workshops with a heterogenous group of stakeholders (Roy et al., 2019; Siddiqui et al., 2019; Wester et al., 2018). Each HKH narratives qualitatively illustrates a unique and plausible socio-economic future for the region considering the interwoven context of social, political, economic, climatic and environmental drivers. The storylines were developed towards 2080 with 2030 and 2050 as important intermediate steps. The multidisciplinary stakeholder group developed two contrasting futures (*Downhill*; pessimistic and *Prosperous*; optimistic) and a moderate (*Business as usual*) storyline.

To integrate the HKH narratives with the basic SSPs we used a matching technique, in which we qualitatively assessed similarities between the regional narratives and global SSP narratives. Matching based on 12 indicators (see Appendix Table A1, for a more elaborate explanation of narrative matching see Kok et al. (2019)) demonstrates that the Prosperous, Business as Usual and Downhill narratives fit well with respectively SSP1, SSP2 and SSP3. The integration created three extended narratives towards 2080; '*SSP1-Proserous*', '*SSP2-Business as Usual*' and '*SSP3-Downhill'* (abbreviated as *SSP1-P*, *SSP2-B* and *SSP3-D* henceforth*)*. This led to the addition of specific migration- and urbanisation storyline elements to the scenarios, and the elaboration of inter-regional cooperation- and governance indicators. The extended narratives provide the qualitative context of the regional scenarios.

Quantitative scaling of basic SSPs

Quantitative country level economic (Dellink et al., 2017) and demographic (Samir & Lutz, 2017) projections have been developed for each of the SSP narratives. However, none of the countries in the Indus basin fall completely within its boundaries. A study by Reimann et al. (2018) used observed growth differences within countries to tailor national SSP projections to smaller regions. Similarly, we used a spatially explicit historical data analysis to scale the basic SSP projections for population and GDP per capita to the Indus basin context. For both indicators we have determined 'basin factors' that represent the historical discrepancy between socio-economic indicators at the national level and for the basin-share of each country and applied these to the basic national SSP projections. It was assumed that these basin factors remain static. The scaled projections form the quantitative core of the regional scenarios.

The scaled population projections were achieved using Equation 1 where P_b is the population for the basin-share of country 'c' at year 'n' for scenario 's', G_{ps} is the SSP national annual population growth rate for country 'c' at year 'n' for scenario 's', and F_{bp} is the basin population factor for country 'c'. F_{bp} was determined by assessing the difference in growth rate between the basin-share of each country and the national average over the period 1990-2015 on the basis of the gridded HYDE 3.2 dataset (Klein Goldewijk et al., 2011). Comparison of the HYDE basin factor with a similar assessment using provincial census statistics for India over the same period yield similar results (see Appendix Table A2). We used the HYDE 3.2 dataset to determine the initial 2015 F_{bp} for the basin-share of every country.

Similarly, the scaled GDP projections were obtained using Equation 2, where E_b is the average GDP per capita in the basin-share of country 'c' at year 'n' for scenario 's', E_{nat} is the national GDP per capita (PPP) at year 'n' for country 'c'; G_{es} is the SSP national annual GDP per capita (PPP) growth rate for country 'c' at year 'n' for scenario 's'; and F_{be} is the basin GDP factor for country 'c'. F_{be} was determined by analysing the present-day difference in GDP per

$$P_b(n,c,s) = P_b(n=2015,\ c) + P_b(n=2015,c) * \left(\prod_{n=2015}^{n} G_{ps}(n,c,s) - 1\right) * F_{bp}(c) \quad (1)$$

$$E_b(n,c,s) = E_{nat}(n=2015,c) * \left(\prod_{n=2015}^{n} G_{es}(n,c,s)\right) * F_{be}(c) \quad (2)$$

capita between the basin-share of each country and the national average. We used the sub-national GDP per capita layer of the DRYAD dataset(Kummu et al., 2018) and the gridded total population layer of the HYDE 3.2 dataset for 2015 to obtain the population weighted difference between GDP per capita in the basin-share of each country and national averages.

To improve the representation of urbanization and population dynamics, available national level urbanisation projections were reviewed (Jiang & O'Neill, 2017). Due to differences in definitions and general lack of consensus on urbanisation patterns in the region, these could not be regionalised further. However, the HKH narratives stipulate that, although the manner and form of urbanisation may differ, the urban population share in the region will increase steeply in any of the plausible futures (Roy et al., 2019), while the SSP projections maintain a low urbanisation trend for developing countries in the economically pessimistic SSP3 variant (O'Neill et al., 2017). Regional projections comparatively suggest that a continuation of the rapid urbanisation trend in the decades to come appears inevitable (Ellis & Roberts, 2015; Siddiqui et al., 2019). Therefore, the low-end SSP3 urbanisation projection was replaced with the mid-range projection of SSP2 in the SSP3-D scenario. For SSP1-P and SSP2-B scenarios the respective basic SSP quantifications were maintained.

Spatialising the regional scenarios
The BasinPop model was used to spatially downscale the regional scenarios. For all three scenarios, the change in population distributions from 2015 towards 2080 was simulated over seven timesteps. The 2015 population density map of the HYDE 3.2 dataset (Klein Goldewijk et al., 2011) was used as the base population map. The socio-economic input data for the starting point and every subsequent timestep were sourced from the quantitative elements of the regionalised scenarios. Other variables and parameters were assessed separately for each scenario by interpreting the regionalised narratives:

- Urban density values were established by adjusting 2015 national urban densities from Cox (2015) with a scenario-specific annual change factor. For Afghanistan no data was available, and the population-weighted basin average was taken. Global patterns of urban densification demonstrate the density of urban areas to first rise steeply and then slowly decreases as the standard of living increases (Klein Goldewijk et al., 2010; Malpezzi, 2013). Urban density in South-Asia is still among the world's highest, but has been decreasing by about 1% per year, as urban growth has geared towards low density sprawl in peripheral areas around major cities (Angel et al., 2011; Ellis & Roberts, 2015). Angel et al. (2011) projects the realistic range of annual urban density decline between 0% and 2% towards 2050. The regional scenarios similarly project high-density urbanization to persist in the foreseeable future in the SSP3-D scenario, while the SSP1-P scenario describes a shift towards planned urban expansion. Therefore, it is assumed that urban density will remain static in the SSP3-D scenario. In the SSP1-P pathway the decrease in urban density is assumed to continue at the 1% annual pace and then accelerate to 2% annually as the standard of living rises. For SSP2-B urban density change was assumed to be a continuation of the current 1% annual decline.
- The maximum allowable population density was assessed using the 2015 extremes of the HYDE dataset. The current maximum within the study area was found within the urban confines of Lahore at around 30.000 people/km^2, while the highest global value is 48.000 people/km^2 in Karachi. It was therefore assumed that in the SSP1-P scenario, the increase of the urban density ceiling is minimal and limited to 32.000 people/km^2 . In the SSP3-D

scenario it was assumed to reach the high-end 48.000 people/km^2 mark. Lastly, in the SSP2-B scenario the maximum density was assumed to be in the middle of the extreme scenarios at 40.000 people/km^2 . This ceiling was scaled at the cell-level by the suitable terrain fraction to obtain the allowable maximum.
- No quantitative estimations could be found on population dynamics near of international borders. Therefore, the suitability of grid cells within the border zone is reduced by 25% in SSP2-B scenario and 50% in the SSP3-D scenario, representing decline in transboundary cooperation. In the 'SSP1-Pros' scenario the effect was omitted.

The scenario-specific weighting of the explanatory variables used for the runs were estimated on the results of the calibration procedure over the historical period. In the SSP2-B scenario, the importance of each variables was assumed to remain constant with the historical patterns found and thus the weightings of the calibration procedure were maintained. For the SSP1-P and SSP3-D scenario, several adjustments were made by interpreting the regionalised narratives:

- The growth of mega cities in South Asia is associated with a lack of economic opportunities in the peripheral areas and the political capital and governance required to steer urbanisation in a more spread out fashion (Jabeen et al., 2017; Kraas, 2007). This is suggested to lead to large shares of dense informal settlements and increasing tendency of migration towards major economic centres. Stronger governance, however, may see urbanisation to be spread out over primary and secondary urban areas alike (Ellis & Roberts, 2015). Therefore, in the SSP3-D scenario the influence of the 'distance to major city' layer was assumed to be 50% higher compared to the SSP2-B scenario, while the influence of the 'distance to urban area' layer was assumed to be 50% lower. In the SSP1-P scenario, the weighting of the 'distance to major city' layer was assumed to be reduced by 50%.
- Highland to lowland migration has historically occurred as a resilience strategy in times of economic downturn (Siddiqui et al., 2019; Tiwari & Joshi, 2015). Hence, this factor was assumed to have an increasing influence in the economically pessimistic SSP3-D pathway, while it is of lesser importance in the SSP1-P pathway. In the SSP3-D scenario it's weighting was therefore increased by 100% compared to the SSP2-B scenario. In the SSP1-P scenario it was reduced by 100%, negating the effect completely.

To assess the influence of these assumptions an uncertainty analysis was conducted for every scenario, consisting of model runs in which the assumed values were individually and collectively scaled by 10% and 20% in both directions (see Figure 2.2D).

2.2.3. Defining resource security thresholds

To determine the influence of socio-economic development on future basin-scale water, food and energy security requirements we use existing national per-capita thresholds for each of the riparian countries. In case no quantitative national thresholds were available, thresholds for the nearest riparian state were used.

Water security

Here, we limit the water security definition to only consider sufficient availability, rather than water demand. Water security thresholds are defined at the national level in Pakistan and India. Both countries distinguish water security in rural and urban areas. Pakistan has set urban water security at 120 litres per capita per day and rural water security at 45 litres per capita per day (Parry, 2016). The rural-urban discrepancy of India's water security definitions is slightly bigger. Here, urban water security is defined at 130 and rural at 40 litres per capita per day (Aayog, 2018). For Afghanistan and China, no national definition could be established. Therefore, the Pakistani guidelines were used.

Food security
We limited the food security definition to only the quantitative availability of sufficient calories. The Indian national dietary guideline distinguishes between the minimum food availability norm for rural and urban areas, based on the more active lifestyles dominant in rural areas. Rural inhabitants are required to have at least 2400 daily kcal available to them, while the urban norm is defined considerably lower at 2100 daily kcal (NIN, 2011). In China the national dietary guideline similarly defines 2320 kcal and 2250 kcal as the threshold for respectively rural- and urban daily caloric availability (Fengying et al., 2010; Liangshu, 2002). Pakistan does not make a distinction based on lifestyle, but uses a bare minimum caloric requirement of 1910 kcal per capita per day and a preferable benchmark of 2350 kcal per capita per day for the general population (Ishaq et al., 2018). For this study, the higher-end threshold was used. The Afghani food security threshold is considerably lower, aiming for at least 2100 kcal per day for every individual (IRA-ME, 2012).

Energy security
Quantitative definitions for energy security at country level are sparse. We limit energy security to domestic electricity requirements, although other energy sources are widely used for domestic purposes in the Indus basin, in particular for cooking. We assume an electricity security threshold of 600 kWh per capita per year for the urban population and 260 kWh per capita per year in the entire Indus basin, based on a study for India (Narula et al., 2017).

2.2.4. Spatial projections

Lastly, the per capita definitions of resource security were combined with the gridded rural and urban population projections to create spatial insight into the change in resource security requirements. The gridded changes in resources requirements were aggregated at district level for Pakistan and India, and the county level of China. To maintain comparability within the basin, in Afghanistan future changes were aggregated at provincial level because of the small geographical area of these administrative units.

2.3. Results

2.3.1. BasinPop model calibration & performance

The calibration procedure at district level found the *distance to urban area* layer to be the most important variable with a weighting at 95. The second most influential variable was found to be *distance to major city* layer at 15, indicating that the district containing major cities have additional pull over regular urban areas. The *terrain suitability* and *distance to main road* layers were both found to have minor influence on population change, at 5 and 2 respectively. The *highland-to-lowland* layer was weighted at 1, thus not influencing the spatial patterns of population change over the historical period.

A comparison of our calibrated model performance to historical census data (see Figure 2.2B, 2.2C) demonstrates that the simulated district level population totals match the observed census data well with a Pearson correlation coefficient of 0.97 and an R^2 of 0.94. The model performance is shown to be best for the high- to moderate-density, predominantly urban districts (Figure 2.2C). Simulated population totals in the highest population districts show a minor overestimation, while the population in districts with lower density are marginally

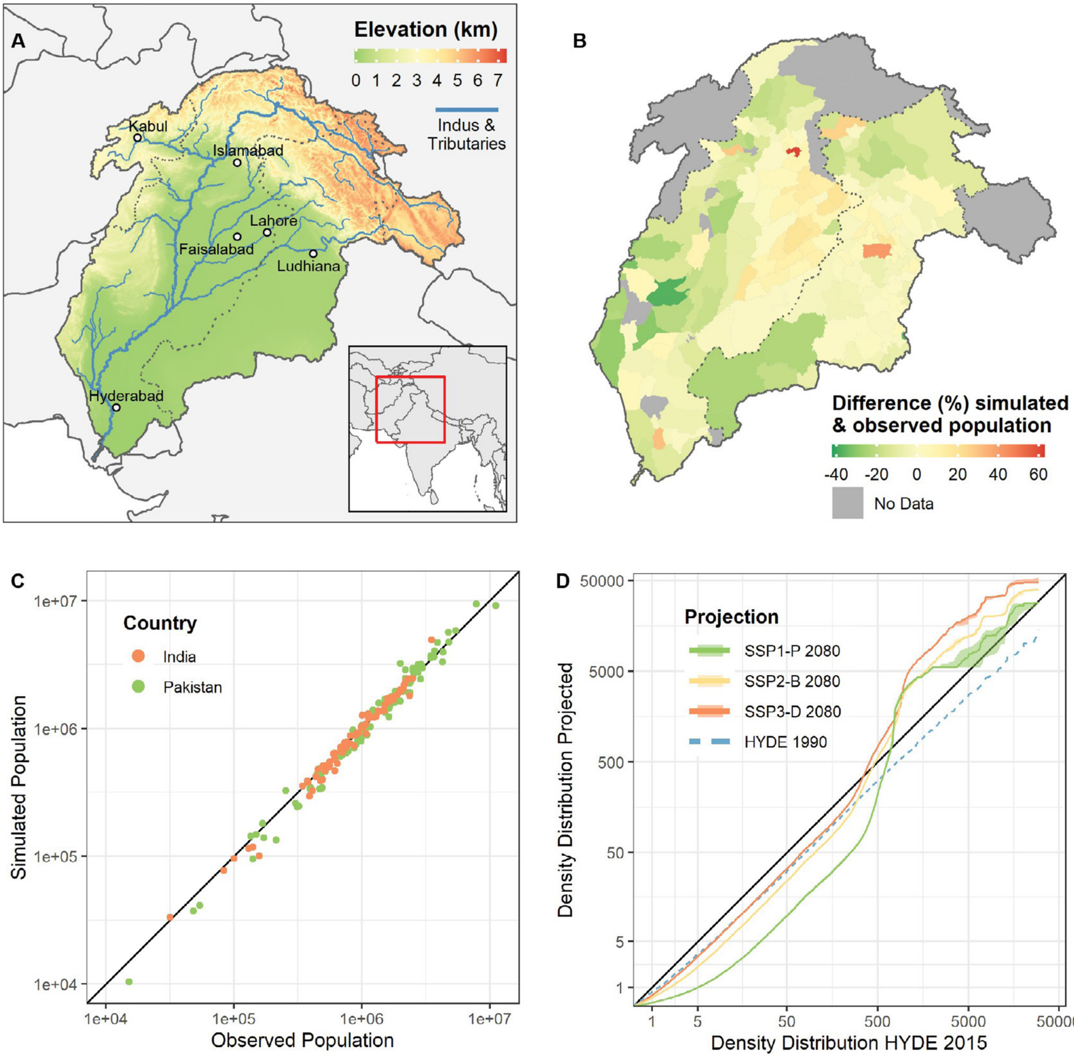


Figure 2.2: map of the study area showing the Indus basin outline, main hydrological network and elevation (A) spatial projection of the difference between simulated population using the BasinPop model and observed census population at district level (B), comparison of simulated versus the observed population at district level (C), the sorted population density of all populated grid cells in the Indus basin for the three scenarios in 2080 and the uncertainty range (shaded) in comparison to the HYDE 2015 baseline (D). The HYDE 1990 distribution is added for reference.

underestimated, especially in Pakistan. A spatial analysis of model performance similarly demonstrates a positive bias towards the densely populated Indus plains and a negative bias in mountain and desert areas. Part of this may well be explained by discrepancies in natural population growth rates, since these are higher in the peripheral areas, but are not considered in the model.

Compared to the 2015 baseline, the projected population distributions in all three scenarios skew towards the high-density grid cells, simulating a gradual urban-rural transition (Figure 2.2D). However, the steepness and form of this transition varies between the scenarios, which shows that the model is capable of simulating various types of urbanisation and migration patterns. The uncertainty analysis (Figure 2.2D) showed that these urban-rural patterns remain consistent under the changes in model parameters and weightings, and that the uncertainty related to the assumed parameters only has a minor influence on the population distribution of high density grid cells.

2.3.2. Indus basin socio-economic scenarios

The regionalisation of the SSPs and the application of the BasinPop model resulted in three spatially explicit regional scenarios (see Table 2.1 and Figure 2.3).

SSP1 - Prosperous

The SSP1-P scenario envisions a region with sustainable economic and social development based on strong international cooperation. Global climate change is contained to a moderate RCP4.5 scenario. Hydro-political tensions in this scenario are considerably lessened, owing to closer trade ties and mutually beneficial economic cooperation between the riparian states. Economic progression is strong, with GDP per capita in the basin increasing as much as thirteen-fold in 2080, driven by rapid technological innovation. Population growth is projected to be comparatively low, peaking at an increase of 40% around the middle of the century, and dropping to 33% by 2080 compared to the 2015 baseline. Urban expansion is comparatively spread out over major cities and secondary cities alike. The majority of Indus basin population is concentrated in sprawling, moderate density patches in the foothills of the high Asian mountain ranges, and on the Indus plains along the river's tributaries (see Figure 2.3B, 2.3E, 2.3H). However, the combination of stagnating population growth and continuing urbanisation have a compounding effect on rural depopulation. This leads to a sharp division in population density between rural and urban areas towards 2080, despite the comparatively low urban density.

SSP2 - Business as Usual

The SSP2-B scenario describes a future in which current processes and patterns are largely sustained. Economic growth maintains its rapid pace and the GDP per capita grows more than eight-fold. Although the pace of population growth steadily decreases, the total number of inhabitants in the basin by 2080 still increases by over 60% compared to the baseline. This increases the pressure on the available resources and inhibits widespread sustainable resource use practices. This scenario faces a moderate to high climate change outlook, corresponding to an RCP6.0 scenario. Despite relatively strong national governments, the historical urbanisation bias towards the basins largest cities continues to dominate this scenario. However, over the course of the scenario, increasing prosperity and the strengthening of governance capacities cause a shift away from concentration in major urban areas towards planned and more spacious urban expansion by 2080. As can be seen in Figure 2.3C, 2.3F and

Table 2.1: qualitative socio-economic context and quantitative figures for Indus basin scenarios.

Scenario Element	Adm.		SSP1-Prosperous			SSP2-Bus. as Usual			SSP3-Downhill		
		2015	*2030*	*2050*	*2080*	*2030*	*2050*	*2080*	*2030*	*2050*	*2080*
Population (millions)	AF	12	16	20	23	17	25	34	19	30	49
	CH	0.028	0.028	0.026	0.022	0.028	0.027	0.023	0.028	0.027	0.023
	IN	84	98	105	92	103	119	120	108	137	171
	PK	169	202	225	218	212	258	288	225	303	412
	Basin.	266	315	351	334	332	402	442	352	470	631
GDP per capita (PPP, billions 2005 USD$)	AF	1327	2 62	7409	30282	1940	4118	14345	1782	2846	5875
	CH	5337	14 65	29299	41919	12751	21151	34437	11662	15417	18076
	IN	5077	12054	31494	71125	10569	21020	45338	9315	12687	16478
	PK	2565	4473	12305	35011	3998	8392	23530	3534	5020	8251
	Basin.	3310	6712	17781	44692	5922	11869	28758	5216	7120	10296
Urbanisation (% of total population living in urban areas)	AF	25	41	58	75	33	43	57	33	43	57
	CH	59	68	81	90	61	70	78	61	70	78
	IN	34	49	67	84	42	53	67	42	53	67
	PK	37	55	70	85	47	58	69	47	58	69
	Basin.	37	52	68	84	45	55	68	45	55	68
Urban Density (cap. per km2)	AF	13888	11944	8838	4861	11944	9794	7247	10242	10242	10242
	CH	6100	5246	3882	2135	5246	4302	3183	6100	6100	6100
	IN	12200	10492	7764	4270	10492	8603	6367	12200	12200	12200
	PK	15800	13588	10055	5530	13588	11142	8245	15800	15800	15800
	Basin.	13888	11944	8838	4861	11944	9 794	7247	10242	10242	10242
Urbanisation patterns	Basin.	-	Decentralized, planned and sprawling			Tendency towards major cities, later sprawling			Strong tendency towards dense megacities		
Migration patterns	Basin.	-	Planned, favourable			Concentration to urban areas			Increasing highland to lowland		
Regional Cooperation	Basin.	-	Constructive cooperation			Sectoral cooperation, but inadequate			Low cooperation, lack of trust, resource conflict		
Global cooperation	Basin.	-	Strong bonds, free trade			Key alliances for resource sharing			More regionalised		
Climate change scenario	Basin.	-	RCP4.5			RCP6.0			RCP8.5		
Innovation	Basin.	-	High			Moderate			Low		
Resource Use Intensity	Basin.	-	Sustainable			Unstable			High and unsustainable		
Water security threshold (L/d/cap.)	AF	120 urban areas / 45 rural areas.									
	CH	120 urban areas / 45 rural areas.									
	IN	135 urban areas / 40 rural areas.									
	PK	120 urban areas / 45 rural areas.									
Food security definition (kcal/d/cap.)	AF	2100 urban & rural areas.									
	CH	2320 urban areas / 2250 rural areas.									
	IN	2100 urban areas / 2400 rural areas.									
	PK	2350 urban & rural areas.									
Energy security definition (kWh/y/cap.)	AF	600 urban areas / 230 rural areas.									
	CH	600 urban areas / 230 rural areas.									
	IN	600 urban areas / 230 rural areas.									
	PK	600 urban areas / 230 rural areas.									

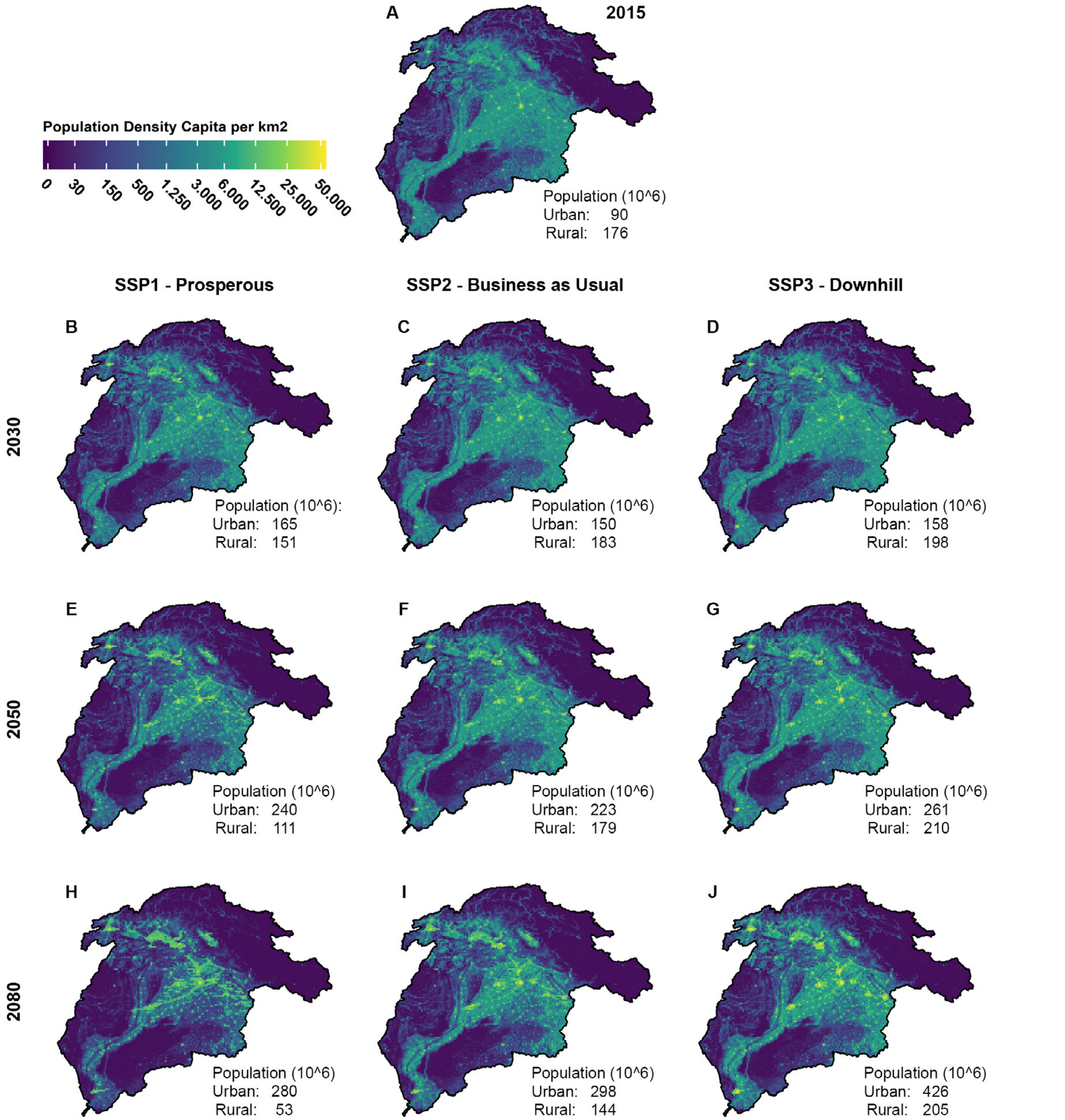


Figure 2.3: Present-day (2015) and simulated future population density in the Indus basin in 2030, 2050, and 2080 for three regional scenarios.

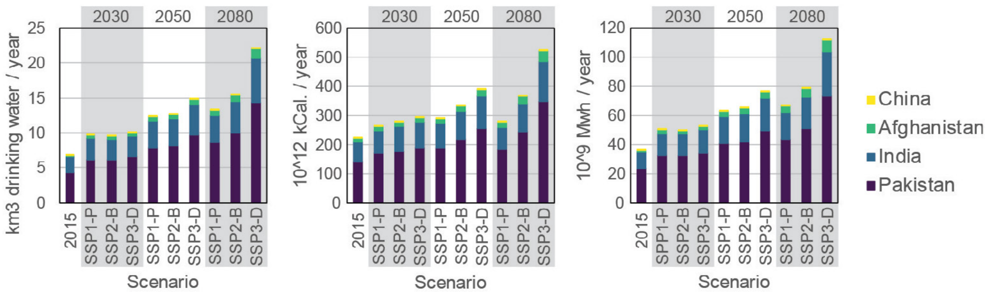


Figure 2.4: Total water, food, and energy security requirements at the basin level for three regional scenarios..

2.3I, this initially leads to the expansion of the basin's major cities, followed by more moderate density expansion around these cities, along the highway network and current secondary urban areas.

SSP3 - Downhill

The SSP3-D scenario imagines a plausible future with meagre economic development and non-abiding tensions between the riparian states. Similar political strife at the global level leads to the inability to control emissions, leading to a strong RCP8.5 climate change scenario. The economic output of the region still progresses, but under pressure from a steep 145% increase in population by 2080, the GDP per capita only increase marginally. Consequently, the standard of living and economic security of the Indus basin inhabitants throughout this scenario remains low. Due to a lack of institutional strength, national governments are unable to steer the patterns of migration and urbanisation trend towards the economically most affluent regions, resulting in a strong concentration towards megacities. The continued rapid population growth and comparatively high population density leads to development of several densely populated clusters around the present-day major cities (see Figure 2.3D, 2.3G, 2.3J). However, population growth is so high that even with the strong urbanisation signal, rural depopulation remains limited. In fact, Afghani rural population density is projected to continue increasing.

2.3.3. Future water, food, and energy security requirements

The combination of the regional socio-economic scenarios with regional resource security thresholds demonstrates that at basin level, water, food and energy requirements will increase in all three scenarios and for all three resources. The requirements for water security demonstrate the steepest growth, increasing by at least 90% in SSP1-P by 2080, but possibly by as much as 220% in SSP3-D, compared to contemporary requirements. This growth is most pronounced in Afghanistan, where drinking water requirements in 2080 in the SSP3-D scenario increase by 390% compared to the 2015 baseline. The energy requirements show a similar increase of between 80% and 200%. The total caloric requirement to achieve food security on the other hand shows only a relatively small increase of 20% in the SSP1-P scenario. However, under pressure from population growth it will more than double in the SSP3-D scenario. The higher growth rate of water and energy security requirements as compared to food security is explained by the former being driven by both population growth and urbanisation. For food security on the other hand, the caloric requirements are slightly higher for rural inhabitants. Urbanisation hence somewhat moderates the effect the population growth on the size of the total food security challenge.

The spatially explicit assessment of future security requirements demonstrates that urbanisation, migration and population growth have a compounding effect on the geographical disparity of water-food-energy requirements (see Figure 2.5). In all three scenarios, resource requirements increasingly converge towards several hot spot regions. The foothills of the Himalayas and the lowlands along the Indus river see the strongest growth in requirements, with district surrounding, or containing, major cities demonstrating exponential increases. Similarly, the areas around Kabul, Afghanistan are projected to require up to six-fold more water and energy resources than they do in the 2015 baseline to meet security requirements. On the other hand, the district located in highland- and desert areas face a reduction in the magnitude of resource security requirements.

2.4. Discussion

2.4.1. Limitations, uncertainties & opportunities

During the development of the BasinPop model, the emphasis was on accurately representing urban expansion because this is the major driver of future water-, food-, energy security challenges (Rasul, 2016). Consequently, the model utilises the same suitability map to spatialise rural and urban population changes. Relevant factors for rural out-migration, however, do not necessarily align with the regionalised factors of urban expansion that form the basis of the suitability maps. For example, the increasing frequency and intensity of heatwaves and drought events due to climate change could affect rural outmigration (Tiwari & Joshi, 2015). However, it is still very uncertain if and how climate change will affect future migration patterns. Further model development could therefore focus on separating the suitability map of rural population change from the suitability map for urban expansion and consider future climatic conditions.

The weighting of BasinPop explanatory variables in this study was based on historical patterns, trends outlined in qualitative regional literature and expert judgement. A rigorous stakeholder engagement approach could be an alternative manner to set the weights. The BasinPop model is highly flexible, has a rapid run-time and visualises results near instantaneous. This makes it suitable to be used for co-creation purposes and to facilitate stakeholders discussions (Biemans & Siderius, 2019) and opens the opportunity to also apply the model as a tool during workshops with regional actors and policymakers. Such an approach may yield additional plausible population maps and build local support in research outcomes. Furthermore, the flexible design of the model does not restrict its usage to the Indus basin. Its architecture can be applied for similar assessment in other river basins.

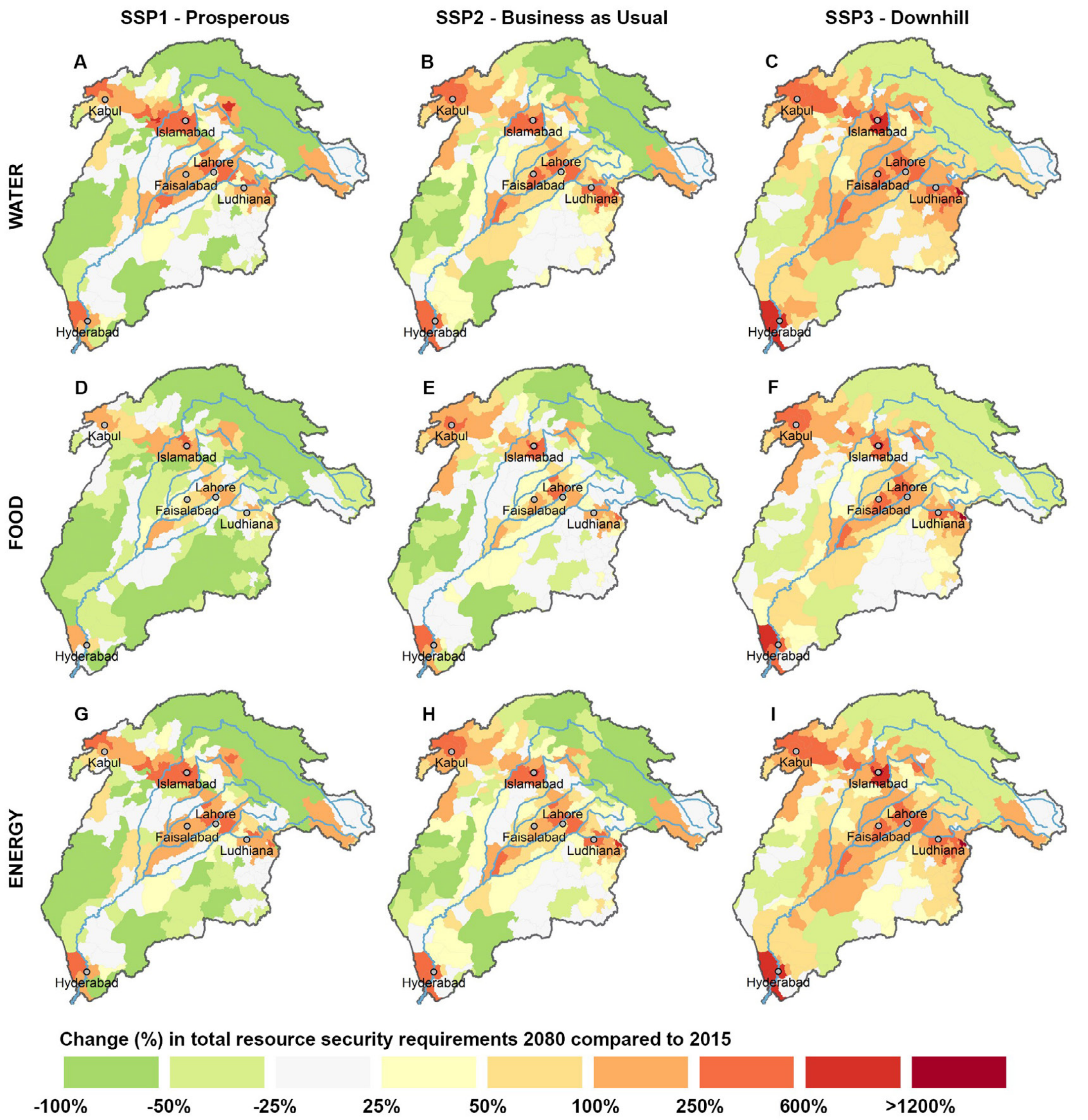


Figure 2.5: change in magnitude of water- (A, B, C), food- (D, E, F) and energy (G, H, I) resources required to attain direct domestic security thresholds in 2080 as compared to 2015.

The indicators used to represent water, food and energy security thresholds were simplified and only reflect the direct quantitative aspect of domestic resource security. However, sufficient resource availability does not mean that wider security goals are met or that resources are distributed equally. For instance, diets must also be sufficiently diverse and nutritious to achieve food security (FAO, 2019). For water resources upstream usage practices may affect downstream water resource availability and quality. Also, due to economic development average per capita demand for water, food and energy resources may grow to considerably surpass the policy-defined security thresholds. For example, per capita domestic water consumption in most developed countries exceeds the highest per capita security requirements of this study, and the riparian states of the Indus basin are projected to follow a similar trend (Bijl et al., 2016). Similarly, the per capita energy consumption in OECD countries at 8000 kWh per capita is more than ten-fold higher than the highest per capita energy-security threshold used in this study (IEA, 2019). The economically driven growth in resource demand may conflict with the universal availability of resources to meet the security requirements. To account for such equity issues, the actual required growth in the domestic availability of water, food and especially energy resources could be considerably higher than the requirements presented in our study, especially in the SSP1-P scenario.

2.4.2. Implications of socio-economic development for the integrated water-food-energy security challenge

Despite the outlined limitations, our scenarios consistently demonstrate resource requirements to increase and spatially concentrate. This indicates that there are several implications of future socio-economic development for the integrated water-food-energy security challenge in the Indus basin.

Foremost, our results show that the water resources required for domestic water security could potentially triple in the Indus basin. Compared to the projected change in water availability at basin scale this still accounts for only a small fraction of the total water budget (Wijngaard et al., 2018). However, due to urbanisation, migration and population growth the increasing requirements will concentrate around the basin's largest cities, with local tenfold increases. Currently, access to safe drinking water in the region is low and a large share of the Indus basin inhabitants source their water locally from groundwater (Mukherji et al., 2018; Rasul, 2016). The groundwater dependency has already led to a substantial drop in urban groundwater tables in Lahore and Islamabad (Basharat et al., 2015). The concentrated exponential surges in domestic water requirements projected in this study could exacerbate local overexploitation of water resources and increase inequity in water access. From a water security perspective, the challenges may therefore not lie with allocating an increasing share of the basin's water resources to growing domestic requirements, but with adapting to the increasing spatial disparity between water supply and demand. The development of improved infrastructure that guarantees universal access to water resources in hotspot areas therefore appears crucial not only from a qualitative water security perspective, but also to ensure sufficient availability.

Our results indicate that food security requirements may rise considerably, potentially doubling under the SSP3-D scenario by 2080. Irrigated agriculture is already the main water user in the Indus basin (Wijngaard et al., 2018) and possibilities for further agricultural land-use expansion in the basin are limited. Additional food production must therefore largely come from intensification of existing agriculture, including the conversion of rainfed to irrigated agriculture. This is likely to require additional blue water resources (Rasul, 2014). However, our scenarios show that considerable urban expansion will occur in the fertile Indus river valleys, encroaching into areas that host the largest share the basin's irrigation system (Wijngaard et al., 2018). To achieve food security it is likely that agricultural water demand will increase in areas where drinking water requirements are also increasing. Urban-agricultural water competition in the basin is already high and an exacerbation of this phenomenon may threaten both water and food security in the Indus basin (Flörke et al., 2018). Our analysis confirms claims by Rasul (2016) that regionally, more food needs to be produced on less land with scarcer water resources.

Finally, satisfying rising energy requirements may also place constrains on water resources. The basin faces energy deficits and has a large untapped hydropower potential (Gernaat et al., 2017). Infrastructure to harvest more of this potential is being developed rapidly (Molden et al., 2014). A promising adaptation avenue may be found in the construction of multi-purpose hydropower dams to increase the control over the allocation of water through space and time. This could potentially benefit water and food security but could have broad scale negative impacts on other sustainability goals such as biodiversity, fisheries and sediment transport. However, projected spatial patterns of population distribution demonstrate that water and energy requirements are increasingly peaking on the Indus plains, while most hydropower potential and production is found in the remote highland areas (Molden et al., 2014). Although hydropower does not directly consume the water, it may aggravate intersectoral water competition and increase pressure on upstream-downstream linkages.

The water-food-energy nexus perspective hence demonstrates that socio-economic development intensifies the complexity of the integrated resource security challenge in two ways; firstly, by increasing the magnitude of future resource security requirements, and secondly by geographically converging the area in which the growing challenge manifests itself. In addition to the temporal convergence of pressure on water-food-energy security due to climate change (Lutz, Immerzeel, et al., 2016), socio-economic development may therefore drive the increasing pressure to also concentrate spatially, rising greatly in several hotspot areas, while staying the same, or even reducing, in other parts of the basin. Further integrated modelling studies and policymaking in the Indus basin must consider the progressive spatiotemporal discrepancy in future resource security challenges when designing adaptation strategies towards achieving the water-food-energy SDGs.

2.4.3. From Global SDGs to Local Indus Development Goals

To better assess what is needed to achieve development goals in the Indus there is a need to define adaptation goals from a more regional perspective. This can be done by translating global Sustainable Development Goals to specific and quantified Indus Basin Development Goals (IDGs). The security requirements presented in this study can provide a quantitative benchmark to monitor the realization of these IDGs. To further define the IDGs, subsequent research could focus on quantifying the second-order nexus resource requirements and adaptation targets (i.e. water-for-food and water-for-energy) within the basin with the help of integrated modelling tools that can account for trade-offs and synergies between them.

2.5. Conclusions

Socio-economic development is an important driver of water, food, and energy resource requirements in the Indus basin. Our results show that under socio-economic development, the urban population of the Indus basin is likely to grow considerably and converge towards the basin's largest cities located in the foothills of the high Asian mountain ranges and the Indus plains. Water and energy security requirements were found to be driven by both population growth and urbanisation, and by 2080 are projected to increase by factor 2.3 (1.9-3.2) and 2.2 (1.8-3.1) respectively compared to the 2015 baseline. The growth of the food requirements over the same period is limited to a factor 1.6 (1.2-2.4), as it is driven only by population growth. However, under the projected changes in population distribution, the weight of resource requirements within the basin was shown to progressively concentrate geographically as well. This drives the magnitude of security requirements in several hotspot areas around the major cities to grow exponentially, while requirements in highland- and desert areas decrease.

The scenario analysis illustrates that socio-economic development has a compounding effect on the complexity of the integrated water-food-energy security challenge of the Indus basin, as it both increases the magnitude of challenges and concentrates them. In this light, adaptation strategies that can moderate the rapidly increasing spatial disparities in interlinked water-food-energy pressure appear essential on the road to achieving the SDGs. The scenarios provide critical input for the robust development of such strategies to be conducted in follow up studies and policymaking. Lastly, the BasinPOP model developed in this study has proven to be a useful and adaptable tool to quantify regional population dynamics. Because of its flexibility it may furthermore be suitable to use in with workshops stakeholders and policy makers. The model architecture may be of use to conduct similar spatially explicit assessment in other complex river basins.

2.6. Acknowledgements

We would like to extend our gratitude dr. Azeem Ali, dr. Hameed Jamali, Arjuna Srinidhi and Samaa Mufti for providing critical insight into the socio-economic context of the Indus basin and reflecting on the implications of our results. Work of all the authors is supported by the SustaIndus project funded by NWO Wotro (Project W 07.30318.002), the Interdisciplinary Research and Education Fund (INREF) of Wageningen University and Research, and Utrecht University.

3. Upstream-Downstream Linkages

Future upstream water consumption and its impact on downstream water availability in the transboundary Indus basin

The densely populated plains of the lower Indus basin largely depend on water resources originating in the mountains of the transboundary upper Indus basin. Recent studies have improved our understanding of this upstream-downstream linkage and the impact of climate change. However, water use in the mountainous part of the Indus and its hydropolitical implications have been largely ignored. This study quantifies the comparative impact of upper Indus water usage, through space and time, on downstream water availability under future climate change and socio-economic development. Future water consumption and relative pressure on water resources vary greatly across seasons and between the various sub-basins of the upper Indus. During the dry season, the share of surface water required within the upper Indus is high and increasing, and in some transboundary sub-basins future water requirements exceed the availability during the critical winter months. In turn this drives spatiotemporal hotspots to emerge in the lower Indus where seasonal water availability is reduced by over 25% compared to natural conditions. This plays an important, but previously not accounted for, compounding role in the steep decline of per capita seasonal water availability in the lower Indus in the future, alongside downstream population growth. Increasing consumption in the upper Indus may thus locally lead to water scarcity issues, and increasingly be a driver of downstream water stress during the dry season. Our quantified perspective on the evolving upstream-downstream linkages in the transboundary Indus basin highlights that long-term shared water management here must account for rapid socio-economic change in the upper Indus and anticipate increasing competition between upstream-downstream riparian states.

Published as: Smolenaars, W.J., Dhaubanjar, S., Jamil, M.K., Lutz, A.F., Immerzeel, W.W., Ludwig, F., Biemans, H. (2022). "Future upstream water consumption and its impact on downstream water availability in the transboundary Indus Basin." Hydrology and Earth System Sciences, 26(4), 861-883.

3.1. Introduction

The Indus basin is shared by Pakistan, India, Afghanistan and China, and is home to over 260 million people (Wada et al., 2019). The basin is among the most depleted and water stressed in the world (Laghari et al., 2012; Wada et al., 2011). The arid plains of the lower Indus basin are densely populated and rely on the largest contiguous irrigation system in the world for their food production. Water demands for irrigation- but also increasingly for domestic and industrial purposes- considerably exceed the dry season supply of freshwater and are compensated for by the overexploitation of groundwater resources (Karimi et al., 2013; Wijngaard et al., 2018). Despite the current overuse of water resources, progress towards achieving the interlinked food-, and water security *Sustainable Development Goals* (SDG 2 & 6 respectively) in the Indus basin is insufficient (Rasul, 2014, 2016). Moreover, the direct- and indirect water resources required to meet these SDGs are projected to increase further under pressure from socio-economic development (Smolenaars et al., 2021; Vinca et al., 2020). Achieving and sustaining the food and water security SDGs in the transboundary Indus basin can only succeed with basin-wide integrated adaptation efforts (Immerzeel & Bierkens, 2012; Immerzeel et al., 2020).

Over 85% of the Indus basin's annual discharge originates from the mountainous and scarcely populated upper Indus (Biemans et al., 2019a), which is shared between all four riparian states. A combination of snowmelt and monsoon rainfall cause mountain water availability across the basin to surge over the Asian summer, while run-off during the dry winter is limited (Laghari et al., 2012). The vast irrigation networks and megacities of the Pakistani and Indian lower Indus plains are therefore highly dependent on the timely provision of mountain water resources (Biemans et al., 2019a; Flörke et al., 2018; Wijngaard et al., 2018), a considerable part of which is transboundary in origin. Previous modelling studies showed that climatic and socio-economic changes may intensify the existing Indus basin upstream-downstream dependencies. Climate change is projected to cause a consistent rise and seasonal shift in upper Indus run-off (Lutz et al., 2014), while population growth, economic progress and urbanization are likely to spur rapid growth of downstream water demands (Biemans et al., 2013; Wijngaard et al., 2018).

Consequently, the Indus basin has been framed as containing strong, one-directional upstream-downstream linkages; the mountainous upper Indus provides and the populous plains of the lower Indus consume water (Khan et al., 2020; Laghari et al., 2012; Reggiani & Rientjes, 2015; Wijngaard et al., 2018). Research investigating the future water resources of the upper Indus basin has accordingly remained largely within the bio-physical domain, exploring the effects of climate change on upstream hydrology and its role as source of water only (Khan et al., 2020; Lutz et al., 2014; Lutz, Immerzeel, et al., 2016; Reggiani & Rientjes, 2015). Regional modelling studies on the influence of anthropogenic activities on the Indus basin water system have likewise focused on the lower Indus basin (Momblanch et al., 2019; Vinca et al., 2020; Wada et al., 2019; Yang et al., 2016), or simply assumed upstream water use activities to be insignificant (Biemans et al., 2019a; Wijngaard et al., 2018). Only Amin et al. (2018) and Mehboob and Kim (2021) explicitly examined the development of water demands in the upper Indus basin. But these studies only covered the upstream parts of the Pakistani share of the basin and did not quantify downstream or cross-border implications.

However, rapid socio-economic development is not limited only to the lower Indus basin. The upper Indus basin also contains fast emerging urban centres (Kabul, Jalalabad, Peshawar, Srinagar, see Figure 3.1) that will place an increasing claim on water resources in the future (Smolenaars et al., 2021). Upstream anthropogenic activities can exacerbate, or even cause, downstream hydrological droughts (Rangecroft et al., 2019; van Loon et al., 2016), especially in basins like the Indus where downstream areas rely heavily on water generated by upstream sources (Zhou et al., 2019). Already now, transboundary water allocation issues in the Indus basin are exacerbating and causing considerable geopolitical tension in the water stressed Kabul sub-basin between upstream areas in Afghanistan and downstream areas in Pakistan (Atef et al., 2019). Global assessments of upstream-downstream linkages in transboundary basins that quantified future dependencies (Munia et al., 2018; Viviroli et al., 2020) and drivers of water stress (Degefu et al., 2019; Munia et al., 2016; Munia et al., 2020) similarly found the Indus basin at considerable risk for future conflicts. Such studies are however based on coarse approaches that aggregate the basin into upstream, midstream and downstream units, and provide limited quantitative insight at the level of individual Indus tributaries where transboundary issues, as seen in the Kabul sub-basin, arise in practice. Socio-economic changes in the upper Indus will thus increasingly affect water availability in both the upper- and lower Indus basin and water sharing between riparian states, but the potential magnitude of their influence throughout the basin is presently unclear.

Transboundary water management and adaptation in the context of the SDGs requires a spatially explicit understanding of the interplay between future water demands and availability, and between upstream and downstream regions (Rangecroft et al., 2019; Yillia, 2016). Additional disaggregated insight into the implications of changing water use activities in the upper Indus on water availability throughout the Indus basin, particularly in relation to climatic changes, is therefore needed. In this study we hypothesize that water consumption in the upper Indus can no longer be ignored, and that it will be an increasingly important driver of transboundary downstream water stress in the coming century. *The aim of this paper is to quantify, both in space and time, the potential impact of upper Indus water consumption on lower Indus water availability accounting for both socio-economic development and climate change.* To do so, validated datasets on Indus hydrology and socio-economic development are combined within a novel water accounting approach that conceptually simulates the complex upstream-downstream dependencies in the transboundary Indus basin. The results provide a first-time quantified perspective on the comparative role of upper Indus socio-economic changes within the broader development of Indus basin upstream-downstream linkages. This insight is important for long-term shared water management between riparian states, adaptation research and hydrological modelling at the basin and sub-basin scales. The approach presents a novel way forward for regionalised upstream-downstream assessments in other complex transboundary river basins.

3.2. Materials and Methods

3.2.1. Case study description: State of water management in the Indus basin

Since ancient times, the water resources of the Indus river and its tributaries have been used extensively for irrigation practices in the fertile lower Indus plains. The current Indus Basin Irrigation System (or IBIS) was first developed around the 1850's and gradually expanded over many decades to become the largest continuous irrigation system in the world. After Partition in 1947, the IBIS, and the upstream areas that provide it with vital water resources, were divided between India and Pakistan. This major change in riparian relations within the Indus basin led to a highly complex transboundary water management setting(Zawahri &

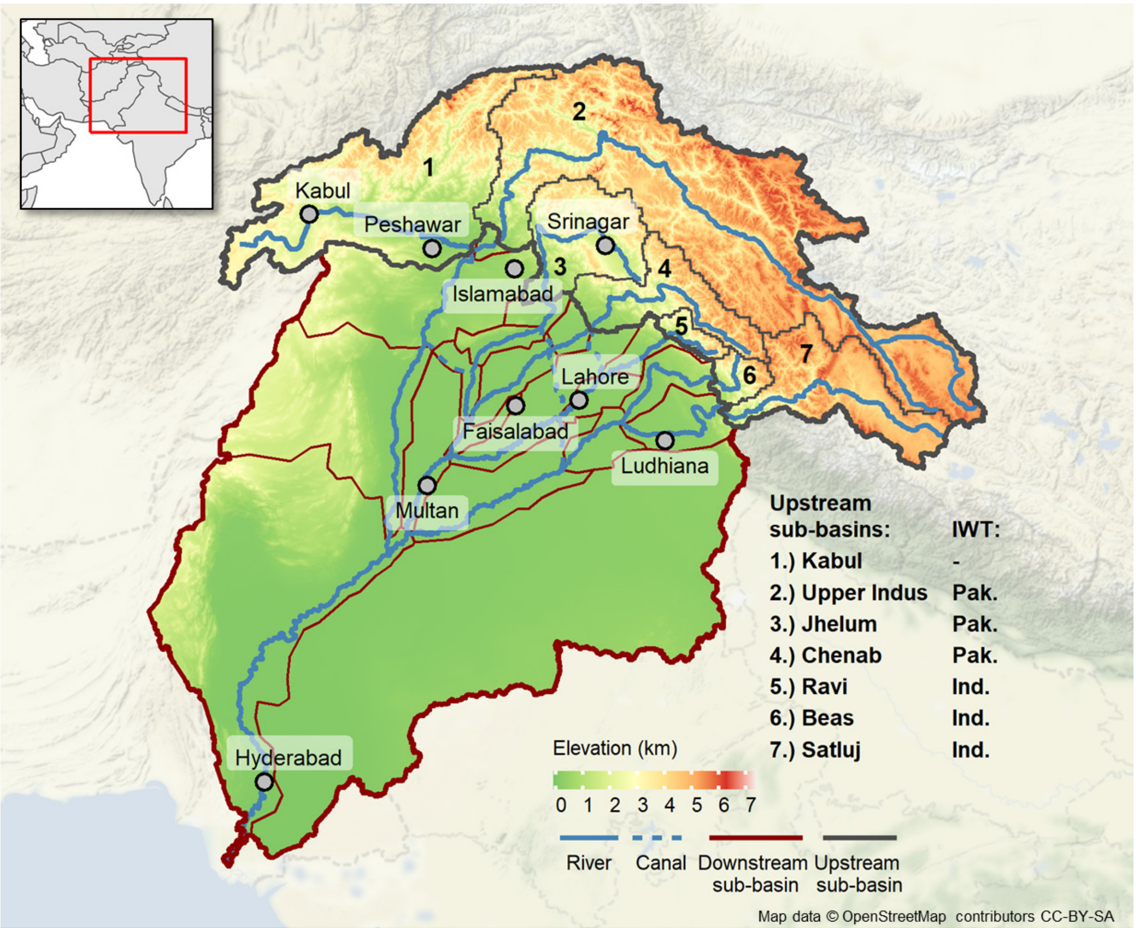


Figure 3.1: Elevation map of the Indus basin with delineation of upper- (numbered) and lower Indus sub-basins, and the allotment of Indus tributaries between India and Pakistan according to the Indus Water Treaty (IWT).

Michel, 2018). In a bid to improve shared water management the World Bank brokered the Indus Water Treaty (IWT) between India and Pakistan in 1960 (Qamar et al., 2019).

The IWT allocates the water resources of the upper Indus between two riparian states (see Figure 3.1), with Pakistan receiving control over the water of the western tributaries (Indus, Jhelum and Chenab), and India over that of the eastern tributaries (Ravi, Beas and Satluj). While this allots a majority of Indus water system discharge to Pakistan (Kalair et al., 2019), the three western tributaries originate in- or cross- the Indian share of the basin before feeding into the lower Indus in Pakistan. The IWT therefore allows limited local water use (e.g. irrigation and domestic purposes) and unlimited non-consumptive use (e.g. run-of-river hydropower and transportation) to upstream India in these tributaries (Zawahri & Michel, 2018). Although the IWT has facilitated three notable transboundary water conflicts and regulated hydropolitical relations for more than six decades, many have pointed out the need to update the framework to meet the new challenges imposed by global change (Parvaiz, 2021; Qamar et al., 2019).

The IWT is not the only treaty governing water management and distribution in the Indus basin. In Pakistan, the Indus water system is the sole source of fresh surface water for the large majority of the country. Water allocation between the provinces of Pakistan is consequently arranged via the Pakistan Water Appointment Accord, which distributes available flow roughly by order of water demand over the four Pakistani provinces(Basharat, 2019). This framework has been shown to work well in high-flow periods, but intra-national disputes have occurred in years of drought, with downstream regions claiming to receive consistently less water than what should be allotted to them (Hassan et al., 2019). Other regions of the Indus basin are not governed by transboundary treaties. The most prominent of these is the Kabul river basin, one of the largest tributaries of the Indus river and a major source of fresh water for both Pakistan and Afghanistan (Qamar et al., 2019). Similarly, upstream China is not part of any water sharing agreement in the Indus basin, but its claim on water resources has so far remained limited due to the low population density and mountainous terrain of its share of the basin (Zawahri & Michel, 2018).

In this study, we used the context of the IWT and shared water management in the Indus basin, as described here, to shape our water accounting approach- both in terms of spatial resolution and in the water use sectors that we consider. In addition, we reflect on the implications that our results may hold for this shared water management context in the discussion section.

3.2.2. Upstream-downstream water accounting approach

To quantify the impact of upper Indus water usage on downstream water availability we used a water accounting approach at the sub-basin level of individual Indus tributaries, and at seasonal timescale. We applied this approach to assess future changes for two integrated climatic and socio-economic change scenarios over the period 1980-2080**.** For both scenarios, our approach consisted of two assessment steps. First, we quantified the development of upper Indus water availability under climate change and subtracted future water consumption. Then, we allocated remaining upstream water over downstream sub-basins and assessed downstream water availability, with and without accounting for upstream consumption. The distribution of remaining water from upstream sub-basins over their respective downstream sub-basins was determined using a novel upstream-to-downstream allocation algorithm developed in this study (see Figure 3.2). Water availability in our approach is operationalised as the per capita available water resources in m^3yr^{-1}, as this accounts for the effect of population changes on the relative water resources available for socio-economic activities (Hanasaki et al., 2018). In the following sections we explain in more detail the spatiotemporal resolution and methods that comprise our approach, and the scenarios and data we used to apply it for our Indus basin assessment.

3.2.3. Spatial and temporal disaggregation

Sub-basin delineation

Previous studies that quantified transboundary upstream-downstream linkages(Degefu et al., 2019; Munia et al., 2016; Munia et al., 2018; Munia et al., 2020), used approaches that divide river basins into two or three sub-basins with a linear flow of water between them. Similarly, our study was also conducted at the sub-basin level. However, instead of assessing the entire upper Indus as one lumped sub-basin, our approach defined sub-basins for each of the main tributaries subject to the IWT (see Figure 3.1 and Section 3.2.1), and the Kabul river. Sub-basins (see Figure 3.1) were delineated using a pour point analysis in ESRI ArcGIS with a 5 arcmin drainage direction map from Hydrosheds (Lehner et al., 2006). First, the upper Indus sub-basins were established by determining the upstream area of the Indus river and its main tributaries. For each river course, the cut-off between upstream and downstream was set at major dams situated within the mountain-to-plain transition zone, which is an often used definition in Indus basin hydrology(Lutz et al., 2014; Lutz, Immerzeel, et al., 2016; Wijngaard et al., 2018). The contributing area upstream from these locations were assessed and resulted in seven sub-basins that were named after their respective main river (see Figure 3.1).

To facilitate the spatially explicit assessment of downstream impacts due to upper Indus water use, the connectivity between the lower Indus and the upper Indus sub-basins needed to be established. Similar to our upstream delineation of sub-basins, we disaggregated the lower Indus basin into multiple sub-basins, based on the overlapping downstream areas of upper Indus sub-basins. Specifically, we delineated lower Indus sub-basins at the confluences of rivers originating from the upper Indus basin. These sub-basins are thus defined by the upper Indus tributaries they receive water from. This allowed our approach to assess which areas within the lower Indus are particularly affected by upstream consumption, whereas beforementioned lumped approaches only provided insight into the upstream-downstream linkage of the basin at large. The distribution of mountain water throughout the lower Indus basin is however highly controlled by an expansive system of barrages and linkage channels(Wescoat Jr et al., 2018). This infrastructure plays a key role in Indus basin water management as it allows riparian states to optimally distribute their scarce water resources(Basharat, 2019). The water flows through the most important linking canals (Indus-Jhelum, Jhelum-Chenab-Ravi-Satluj and Chenab-Ravi, see Figure 3.1) were therefore also considered in the delineation of downstream sub-basin and the designation of the downstream area of upper Indus sub-basins. This approach resulted in eighteen lower Indus sub-basins that each receive water resources from a unique combination of upper Indus sub-basins (see Figure 3.1).

Seasonality and timeframe

The strong seasonal character of Indus hydrology requires water resource assessments to be conducted at the seasonal level(Laghari et al., 2012). Therefore, contrary to the annual level of previous studies(Munia et al., 2016; Munia et al., 2018; Munia et al., 2020; Viviroli et al., 2020) we aggregated and analysed hydrological changes and impacts for the two hydrological seasons suggested by Laghari et al. (2012), that correspond with the main agricultural season; the *Dry season* (Rabi cropping season, Nov-Apr) and the *Wet season* (Kharif cropping season, May-Oct). Additionally, for some analyses the seasons were disaggregated further to the four climatological seasons used in other regional water system studies(Rajbhandari et al., 2015; Wijngaard et al., 2018); *Pre-monsoon* (Mar-May), *Monsoon* (Jun-Aug), *Post-monsoon* (Sep-Nov) and *Winter* (Dec-Feb). To illustrate the progression of water consumption and availability over time, data was assessed as transient annual timeseries or for three assessment timesteps; the 1980-2010 historical reference period (Ref), and the future 2030-2050 (Mid) and 2060-2080 (Late) periods.

3.2.4. Integrated scenarios

Both climate and socio-economic change might increase pressure on available water resources. To obtain insight into potential future changes in upstream-downstream linkages and impacts, we defined two regional scenarios that integrate socio-economic development and climate change. The socio-economic core of the scenarios was sourced from a set of regionalised and spatially downscaled *Shared Socio-economic Pathways* ('SSPs', see O'Neill et al. (2014)) specifically downscaled towards 2080 for the Indus basin by Smolenaars et al. (2021). The optimistic 'SSP1-Prosperous' (sustainable economic progress and low population growth, hereafter: SSP1) and the pessimistic 'SSP3-Downhill' (fragmented economic stagnation and high population growth, hereafter: SSP3) storylines were selected, as these provided the highest contrast and thus the broadest plausible bandwidth of results.

The socio-economic storylines are regionally downscaled extensions of the global SSP storylines and could therefore be consistently matched with the RCP emissions framework(van Vuuren et al., 2014). To represent future climatic conditions we combined the SSP1 and SSP3 storylines with respectively the moderate RCP4.5 and extreme RCP8.5 emission scenarios. This resulted in two future scenarios for climate, population and GDP: SSP1-RCP4.5 and SSP3-RCP8.5 (hereafter referred to as SSP1 and SSP3).

3.2.5. Upstream-downstream assessment and data sources

Scenario forcing data

Applying the two integrated scenarios within our quantitative upstream-downstream approach required us to obtain spatially explicit climatic and socio-economic forcing data for our scenarios (see Table 3.1). For the socio-economic storylines, spatially explicit future population projections towards 2080 at 5 arcmin (~8 km) resolution are available that account for population growth and urbanisation, as well as downscaled GDP projections(Smolenaars et al., 2021). For the 1980-2010 reference period, we used the 5 arcmin population maps of HYDE project (Klein Goldewijk et al., 2011). Historical GDP data was obtained from IIASA(Dellink et al., 2017). Climate change projections at daily timescale for the coupled RCP emission scenarios were obtained from eight (four per RCP) downscaled GCM projections for the wider South Asia region at 5 arcmin resolution over the period 1980-2100 (Lutz, ter Maat, et al., 2016).

Determining the impact of upper Indus water consumption on remaining water availability

As the first assessment step of our approach, we determined for both scenarios the progression of water consumption in the upper Indus basin in relation to the change in water availability under socio-economic development and climate change. For the upper Indus sub-basins, daily natural discharges were determined at the sub-basin outlets (i.e. the absolute surface water availability per sub-basin). Validated high-resolution discharge projections for the seven upper Indus sub-basins were used at daily timesteps for the reference period and for both RCPs (1980-2100) (Wijngaard et al., 2018; Wijngaard et al., 2017). These projections are generated by the distributed *Spatial Processes in Hydrology* (SPHY) cryosphere–hydrology model based on the same downscaled climate forcing data that pertains to the climatic scenarios of this study. The SPHY model was developed specifically to simulate the glacier-dominated hydrology of High Mountain Asia and has been often been applied for the Indus basin (Biemans et al., 2019a; Lutz et al., 2014; Lutz et al., 2019).

Subsequently, we decreased the daily natural discharges with daily aggregated consumptive water requirements for the domestic, industrial and agricultural sector of each sub-basin to estimate actual discharge. Consumptive water requirements were defined as the sectoral water demands, minus the return flows(Bijl et al., 2016), which represent the amount of natural water resources that are made unavailable for downstream usage. Consumptive water requirements in excess of daily surface water availability were assumed to be stored within the sub-basin in the closest preceding days with surplus discharge and released on the day shortages occurred. The difference between natural and actual outflow of upper Indus sub-basins therefore always equalled the consumptive requirements at the annual level, but for daily timesteps these occasionally varied. Sectoral consumption data were obtained from the following sources:

- Domestic and industrial consumptive water requirements projections for the upper Indus basin were obtained with the regression models of Bijl et al. (2016). The models simulate annual water consumption intensity per sectoral unit (capita and $US of GDP respectively) as a product of economic development (expressed in GDP per capita) increasing efficiency through time, and a pre-calibrated 'region-factor' that accounts for climatological and cultural circumstances (see Appendix B). The models were forced for each basin-country with the national-level GDP per capita projections of the scenario forcing data. As the Bijl models provided an annual consumption value, daily consumptions were assumed to be 1/365th of the annual output and thus to not vary within the projected year. The simulated daily consumption intensities were multiplied by the projected total population and GDP of the basin-share of each country, and then spatially distributed over the gridded population projections of the scenarios. Population data for both the reference and projected periods was available at 10 year timesteps in the forcing dataset. To obtain annual values the data was linearly interpolated between these timesteps. Lastly, the gridded consumption data was summed for each upper Indus sub-basin.
- To obtain water usage data for the agricultural sector the grid-based integrated crop production-hydrology Lund–Potsdam–Jena managed Land (LPJmL) model was used. LPJmL simulates water balance and crop production for twelve crops (irrigated and rainfed), and the interaction between them, whilst considering for climatic circumstances and anthropogenic interventions(Bondeau et al., 2007). This allows the influence of crop production on the water system to be quantitatively untangled and studied under climatic and socio-economic changes(Gerten et al., 2011; Rost et al., 2008). For this study a regional LPJmL version was used that was developed specifically to represent the monsoon-dominated double-cropping systems of South Asia at 5 arcmin resolution (see Biemans et al. (2019a)). The South-Asia LPJmL version has been applied for multiple integrated assessment that include the Indus basin(Biemans et al., 2019a; Wijngaard et al., 2018) and its agricultural water withdrawals have been validated for the broader South Asia region(Biemans et al., 2016; Biemans et al., 2013). The LPJmL simulations were conducted with unlimited groundwater access for irrigation, providing an estimate of the potential

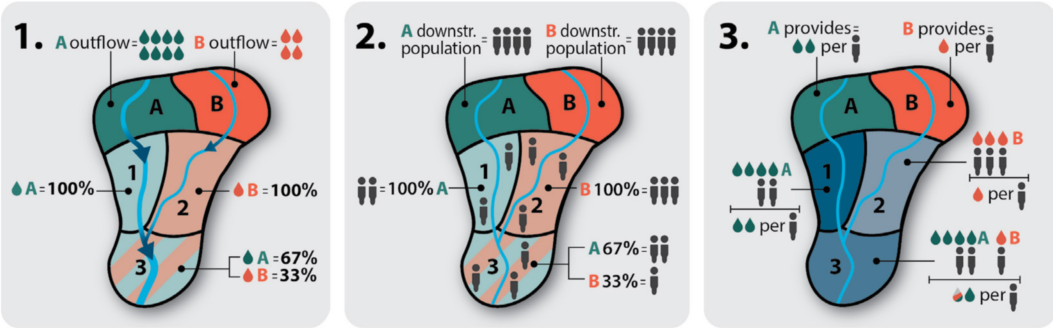


Figure 3.2: Conceptual representation of the allocation of upstream sub-basin water resources to downstream sub-basins. First, (1) the relative contribution of each upstream sub-basin to the total upstream inflow of each downstream sub-basin is determined. Next, (2) the population of each downstream sub-basin is determined and assigned to the upstream sub-basins by their relative flow contribution. Lastly, (3) upstream outflows are divided by their total assigned downstream populations to obtain the per capita upstream water availability they provide to the downstream sub-basins. The upstream per capita water availability per downstream sub-basin is the mean per capita availability provided by all contributing upstream basins, weighted by their assigned populations. The total per capita water availability of a downstream sub-basin is determined by aggregating the local downstream per capita water availability and the upstream per capita water availability.

Table 3.1: Input datasets used for water accounting analysis.

Input dataset	Resolution (time/space)	Source
Discharge		
Upper Indus	Daily 1980-2100/ Sub-basin outlet	Wijngaard et al. (2017)
Lower Indus	Daily 1980-2080/ 5 arcmin	Simulated by this study, model and calibration from Bondeau et al. (2007) & Biemans et al. (2016)
Consumption		
Domestic	Annual 1980-2080/ National level	Simulated by this study, model and calibration from Bijl et al. (2016)
Industrial	Annual 1980-2080/ National level	Simulated by this study, model and calibration from Bijl et al. (2016)
Agricultural	Monthly 1980-2080/ 5 arcmin	Simulated by this study, model and calibration from Bondeau et al. (2007) & Biemans et al. (2016)
Scenarios		
Population projections	Annual 1980-2080/ 5 arcmin	Smolenaars et al., (2021) for future (2015-2080) & Klein Goldewijk et al. (2011) for historical (1980-2015)
GDP projections	Annual 1980-2080/ National level	Future (2015-2080) Smolenaars et al., 2021 & historical (1980-2015) Dellink et al. (2017)
Climate data	Daily 1980-2100/ 5 arcmin	Lutz, ter Maat, et al. (2016)

agricultural water consumption. This avoids inconsistencies with the discharge data obtained from the SPHY model. LPJmL was forced with the downscaled climate data pertaining to the scenario dataset and with regional land-use based on land-use change projections for SSP1 and SSP3 from the IMAGE integrated assessment model (Stehfest et al., 2014). The land-use projections were constructed at 5 arcmin resolution by applying the IMAGE growth-rates for rainfed and irrigated crops to 2005 land-use extents from the spatially explicit MIRCA-2000 dataset(Portmann et al., 2010), an approach that is often used for scenario based studies with LPJmL(Wijngaard et al., 2018). The daily consumptive water requirements were determined by aggregating the blue water consumption (i.e. evapotranspiration originating from blue water (surface and groundwater) resources) of agriculture from evapotranspiration and conveyance losses and summing these per sub-basin. Surface water in LPJmL is only extracted if there is a soil moisture deficit. This agricultural green water footprint (i.e. evapotranspiration originating from green water (precipitation) resources), was not considered in the total agricultural water usage, as the SPHY discharge projections already account for green water evapotranspiration through a natural vegetation layer (Wijngaard et al., 2017).

To further interpret the consequences of climatic- and socio-economic changes on the status of water availability in the upper Indus basin the APC (Availability Per Capita) index(Hanasaki et al., 2018) was applied, which is an expanded version of the well-known Falkenmark index(Falkenmark et al., 1989). The APC index assesses the annual available water resources per capita and categorises these by the degree to which water scarcity is limiting a society:

- No water stress: >5000 m^3 per capita per year
- Low water stress: 5000-1700 m^3 per capita per year
- Moderate water stress: 1700-1000 m^3 per capita per year
- High water stress: 1000-500 m^3 per capita per year
- Extreme water stress: <500 m^3 per capita per year

Lastly, the impact of upper Indus consumption on environmental flows was studied using the *variable monthly flow* (VMF) method as applied by Pastor et al. (2019). VMF defines that a minimum of respectively 30% and 60% of mean natural flows in the dry and wet seasons must be maintained for environmental well-being. Thus, only 70% and 40% of water resources during the wet- and dry season can sustainably be consumed(Pastor et al., 2014). Minimum daily flow thresholds were determined for the mean daily flows over the historical reference period (1980-2010) and the wet and dry season definition by Laghari et al. (2012). The status of environmental flows was expressed as the days per year in which minimum flows are not met at the outlet of upper Indus sub-basins.

Quantifying upstream-downstream linkages and impacts

For the second assessment step of our approach we quantified the impact of upper Indus consumption on water availability in the lower Indus. This step required surplus water resources in upper Indus sub-basins to be allocated over the lower Indus sub-basins. Previous studies (Degefu et al., 2019; Munia et al., 2016; Munia et al., 2018; Munia et al., 2020) used a linear method for this upstream-to-downstream water allocation, meaning that surplus water flows from an upstream sub-basin to one fixed downstream sub-basin. However, our water accounting approach considered for multiple upstream sub-basins, with an overlapping mesh of downstream sub-basins. We moreover accounted for linkage channels (see section

3.2.3) when defining the downstream area of each upper Indus sub-basin. This means that the downstream distribution of surplus upstream water is not only based on natural flow direction, but is also demand based and thereby inherently variable. Beforementioned linear methods were thus not suitable to simulate upstream-to-downstream water allocation in our regionalised approach.

We therefore developed a new routine (see Figure 3.2) that works similar to the approach of Viviroli et al. (2020), which distributes surplus upstream water resources equally over all downstream grid cells. Instead of distributing surplus upstream water on the basis of geographical area, however, we distributed it based on population, as we think this is a better proxy for where water demand is located. Our upstream-downstream water allocation algorithm assumes an equitable distribution of upper Indus outflows among the downstream population of each upper Indus sub-basin. Populations of lower Indus sub-basins that are downstream from multiple upper Indus sub-basins were divided and assigned to upstream sub-basins relative to the water supplied (see Figure 3.2). This allowed for the simultaneously allocation of upstream-downstream water resources for all upper Indus sub-basins, without having to make quantitative assumptions as to how water is distributed between multiple competing downstream sub-basins.

We applied this upstream-to-downstream allocation routine for the three assessment timesteps (Ref, Mid and Late). First, the average natural flow and average actual flow were determined per season and then distributed over the lower Indus sub-basins. The allocation procedure used the spatially explicit population projections of the scenario forcing data set as population input data for lower Indus sub-basins. The total water availability of each lower Indus sub-basin was then determined by aggregating, for each timestep and season, the allocated upper Indus water resources with average water supply generated within the lower Indus sub-basin itself. Hereby, it was assumed that all water resources generated in a lower Indus sub-basin are utilized within that sub-basin. The water resources originating locally in the lower Indus sub-basins were determined with the LPJmL model. Simulations were ran with naturalized upstream inflow, natural vegetation and without anthropogenic water withdrawals, an approach that is often used to determine natural flows (Jägermeyr et al., 2017; Rost et al., 2008). The model was forced with the downscaled climate data of the respective scenarios. For each of the lower Indus sub-basins, the discharges at its outlet were assessed and the inflows from outside the sub-basins were extracted (i.e. the discharges at the outlets of sub-basins directly feeding into a sub-basin), thus leaving only the water generated within the sub-basin itself.

The impact of upper Indus consumption on lower Indus water availability was then studied by comparing relative differences in total seasonal water availability between the actual and natural flow conditions for each timestep. As availability between seasons and sub-basins varied greatly, the absolute and annual based APC index was not suitable for this analysis. Water availability in the future timesteps was additionally compared to reference period availability to assess the change in lower Indus water availability through time under integrated climate change and socio-economic development. This provided insight into the comparative role of upper Indus water consumption. Similarly, per capita water availability in the lower Indus in our approach was also affected by population growth, and by climate change through its effect on discharges. We therefore additionally assessed water availability in lower Indus sub-basins was for future timesteps with downstream population distributions and climatic conditions independently kept in reference period conditions (i.e. with population maps and discharges as they were in the Ref 1980-2010 timestep). This allowed the isolated effects of respectively climate change and downstream population changes on future water availability in the lower Indus to also be quantified and compared to the impact of upper Indus consumption.

3.3. Results

3.3.1. Changes in upper Indus water consumption

Figure 3.3B shows that the reference period total water consumption in the upper Indus basin is around 6.9 $km^3\ yr^{-1}$ (compared to approximately 140 $km^3\ yr^{-1}$ in the lower Indus basin (Wijngaard et al., 2018)) Water use activities are mostly located in the Kabul, Indus and Jhelum sub-basins and are dominated by agricultural water use during the wet season. The population in the upper Indus is projected to grow by 124% and 245% towards 2080 in SSP1 and SSP3 respectively (Table 3.2, compared to reference period 1980-2010). The highest population growth will be in the Kabul sub-basin (188% in SSP1 and 350% in SSP3), especially in the Afghani share (Smolenaars et al., 2021). This sub-basin contains three large cities, two of which in Afghanistan, that are projected to expand rapidly due to the strong urbanization trends (see Figure 3.3A). Water consumption in the upper Indus subsequently demonstrates an annual growth to 13 $km^3\ yr^{-1}$ (88%, SSP1) and 17 $km^3\ yr^{-1}$ (146%, SSP3) in the 2060-2080 period. Consumption increases are largely concentrated in sub-basins that already account for the majority of present water usage. The Kabul and Jhelum sub-basins are projected to face annual water use increases of respectively as much as 135% and 307% in the SSP3 late period, with this growth largely located in the respective Afghani and Indian parts.

The projected growth in water consumption is highest for the domestic sector (figure 3.3B). Population growth and economic progress are projected to increase both the number of end-users and the amount of consumed water resources per end-user. Economic growth similarly drives an increase in the industrial water use. Agricultural water use only increases slightly from present day values as expansion options in the mountainous upper Indus are limited and higher temperatures due to climate change reduce the length of the growing season of staple crops (Wijngaard et al., 2018). The relative growth in the domestic- and industrial water use-dominated dry season (179% in SSP1 and 296% in SSP3) is therefore greater than in the wet season (60% in SSP1 and 102% in SSP3) and the annual average (see Appendix Figure B3). Figure 3.3 shows that the seasonal difference in water consumption in the upper Indus basin is accordingly projected to decrease by the late period in both scenarios.

3.3.2. Impact of climatic and socio-economic changes on upper Indus water resources

Table 3.2 demonstrates that the ensemble mean annual flow of the upper Indus increases by 38% and 32% respectively in the SSP1 and SSP3 scenarios for the 2060-2080 period. The heightened discharge is consistent between the two scenarios, as both predict temperatures in South Asia to increase (~2°C in RCP4.5 and ~5°C in RCP8.5, see (Lutz, ter Maat, et al., 2016)), which drives increased glacial melting until at least the end of the century (Wijngaard et al., 2017). The relative increase is most pronounced in the dry season. The development of discharge does nonetheless vary greatly between the sub-basins. The Satluj and Indus sub-basins are projected to face annual flow increases of up to 54% and 51% respectively, while those of the Kabul and Jhelum sub-basins stay roughly similar over the projected period.

Despite the general increase in surface water availability, the mean annual per capita water availability in the upper Indus basin is projected to drop by 43% (SSP1) and 65% (SSP3) by

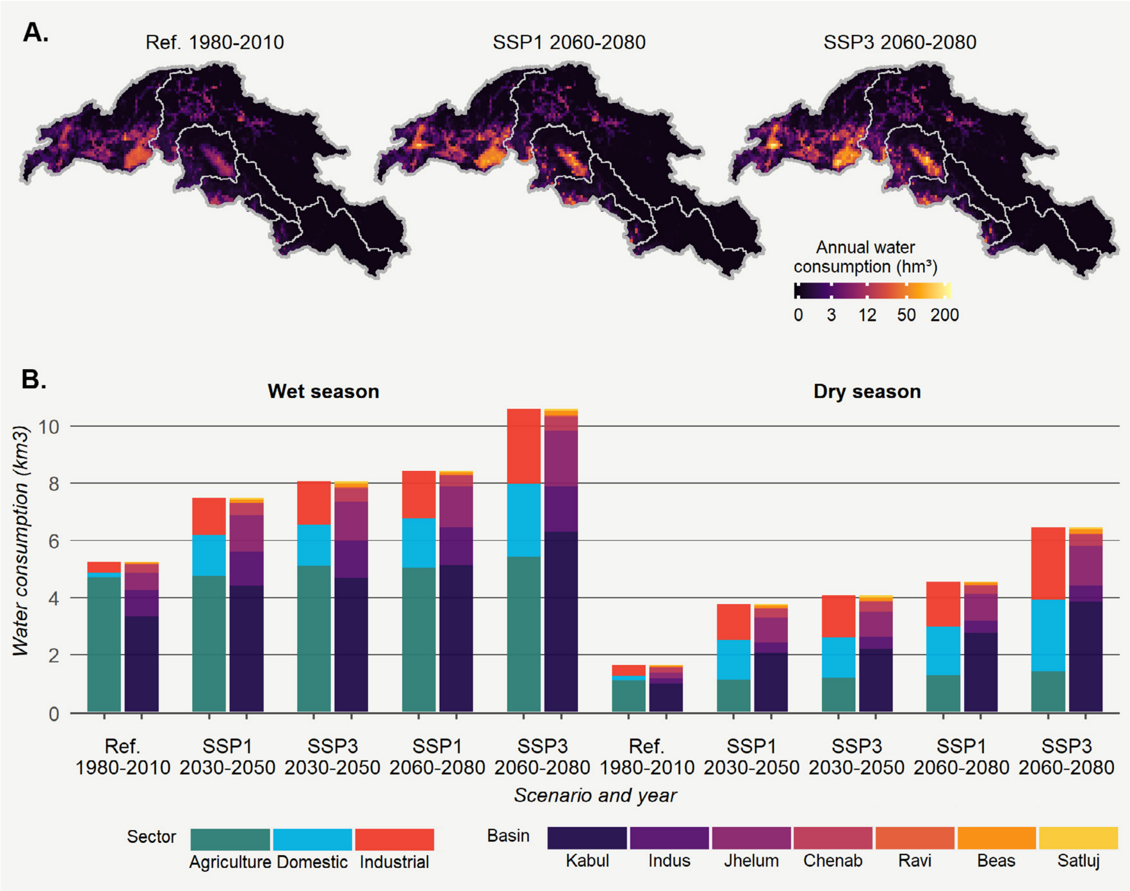


Figure 3.3: Spatially (A.), seasonally and sectoral (B.) disaggregated water consumption in the sub-basins of the upper Indus basin. Agricultural water use is based on the ensemble mean. The total height of the bars (B.) indicates total water use in the upper Indus.

Table 3.2: Development of population, water consumption and natural flow (ensemble means) for the upper Indus sub-basins (relative change between brackets) for the reference (1980-2010) mid (2030-2050) and late (2060-2080) period.

Sub-basin	**Population (millions)**				
	Ref.	*Mid.*		*Late.*	
	-	*SSP1*	*SSP3*	*SSP1*	*SSP3*
Kabul	16	40 (150%)	47 (194%)	46 (188%)	74 (363%)
Upper Indus	4.5	6.9 (53%)	8.1 (80%)	6.2 (38%)	9.4 (109%)
Jhelum	7.9	16.9 (113%)	17.1 (116%)	16.6 (110%)	23.1 (192%)
Chenab	2.6	3.9 (50%)	4.4 (69%)	3.0 (15%)	4.7 (81%)
Ravi	0.33	0.26 (-21%)	0.41 (24%)	0.11 (-66%)	0.31 (-6%)
Beas	0.95	1.4 (47%)	1.7 (79%)	1.4 (47%)	2.0 (110%)
Satluj	0.68	0.82 (20%)	1.1 (62%)	0.58 (-15%)	1.2 (76%)
Total	33	70 (112%)	80 (142%)	74 (124%)	114 (245%)
	Water consumption (km3)				
Kabul	4.3	6.5 (51%)	6.9 (60%)	7.9 (84%)	10 (135%)
Upper Indus	1.1	1.6 (45%)	1.7 (55%)	1.7 (55%)	2.2 (100%)
Jhelum	0.81	2.1 (159%)	2.3 (184%)	2.4 (196%)	3.3 (307%)
Chenab	0.48	0.74 (54%)	0.83 (73%)	0.67 (40%)	0.91 (90%)
Ravi	0.03	0.05 (35%)	0.066 (91%)	0.03 (-3%)	0.06 (71%)
Beas	0.09	0.19 (111%)	0.23 (156%)	0.18 (100%)	0.29 (222%)
Satluj	0.05	0.11 (104%)	0.15 (178%)	0.09 (70%)	0.17 (215%)
Total	6.9	11 (64%)	12 (77%)	13 (88%)	17 (146%)

	Natural flow (km3)									
	Dry	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*	*Dry*	*Wet*
Kabul	7.5	42	8.3 (11%)	47 (12%)	9.2 (23%)	42 (0%)	8.7 (16%)	47 (12%)	10 (33%)	37.7 (-10%)
Upper Indus	5.2	63	7.8 (50%)	100 (59%)	8.7 (67%)	94 (49%)	7.4 (42%)	98 (56%)	10 (92%)	93 (48%)
Jhelum	5.3	25	5.9 (11%)	28 (12%)	6.2 (17%)	26 (4%)	6.4 (21%)	28 (12%)	7.2 (36%)	25 (0%)
Chenab	3.0	23	4.1 (37%)	32 (39%)	4.6 (53%)	32 (39%)	4.3 (43%)	33 (43%)	5.2 (73%)	31 (35%)
Ravi	1.1	7.9	1.5 (36%)	8.4 (6%)	1.6 (45%)	8.4 (6%)	1.6 (45%)	8.6 (9%)	1.8 (64%)	8.2 (4%)
Beas	1.3	7.6	1.7 (31%)	10 (32%)	1.7 (31%)	9.9 (30%)	1.9 (46%)	10 (32%)	1.9 (46%)	10 (32%)
Satluj	2.5	49	4.4 (76%)	72 (47%)	4.7 (88%)	71 (45%)	5.2 (108%)	77 (57%)	6.4 (156%)	73 (49%)
Total	26	218	34 (31%)	297 (36%)	37 (42%)	284 (30%)	35 (35%)	302 (39%)	43 (65%)	278 (28%)

Table 3.3: Development of water availability (ensemble means) for the upper Indus sub-basins (relative change between brackets) for the reference (1980-2010) mid (2030-2050) and late (2060-2080) period. The occurrence of water stress (m3/cap/year < 5000m3) in a sub-basin is indicated by providing the values in italics. Moderate water stress (m3/cap/year < 1500m3) is additionally indicated with * and severe water stress (m3/cap/year < 1000m3) with **.

Sub-basin	**Water availability (m3/cap/year)**				
	Ref.	*Mid.*		*Late.*	
	-	*SSP1*	*SSP3*	*SSP1*	*SSP3*
Kabul	*3090*	*1380* (-55%)*	*1090* (-65%)*	*1210* (-61%)*	*640** (-79%)*
Upper Indus	15160	15620 (3%)	12680 (-16%)	17000 (12%)	10960 (-28%)
Jhelum	*3840*	*2010 (-48%)*	*1880 (-51%)*	*2070 (-46%)*	*1390* (-64%)*
Chenab	10000	9260 (-7%)	8320 (-17%)	12430 (24%)	7700 (-23%)
Ravi	27270	38080 (40%)	24390 (-11%)	92730 (240%)	32260 (18%)
Beas	9370	8360 (-11%)	6820 (-27%)	8500 (-9%)	5950 (-36%)
Satluj	75740	93170 (23%)	68820 (-9%)	141720 (87%)	66170 (-13%)
Total	7380	*4720 (-36%)*	*4010 (-46%)*	*4560 (-38%)*	*2790 (-62%)*
	Water availability- only pop. change (m3/cap/year)				
Kabul	*3090*	*1240* (-60%)*	*1050* (-66%)*	*1080* (-65%)*	*670** (-78%)*
Upper Indus	15160	9880 (-35%)	8420 (-44%)	11000 (-27%)	7260 (-52%)
Jhelum	*3840*	*1790 (-53%)*	*1770 (-54%)*	*1830 (-52%)*	*1310* (-66%)*
Chenab	10000	6670 (-33%)	5910 (-41%)	8670 (-13%)	5530 (-45%)
Ravi	27270	34620 (27%)	21950 (-20%)	81820 (200%)	29030 (6%)
Beas	9370	6360 (-32%)	5240 (-44%)	6360 (-32%)	*4450 (-53%)*
Satluj	75740	62800 (-17%)	46820 (-38%)	88790 (17%)	42920 (-43%)
Total	7380	*3470 (-53%)*	*3050 (-59%)*	*3290 (-55%)*	*2120 (-71%)*
	Water availability – only climate change (m3/cap/year)				
Kabul	*3090*	*3460 (12%)*	*3200 (4%)*	*3480 (13%)*	*2980 (-4%)*
Upper Indus	15160	23960 (58%)	22820 (51%)	23420 (54%)	22890 (51%)
Jhelum	*3840*	*4290 (12%)*	*4080 (6%)*	*4350 (13%)*	*4080 (6%)*
Chenab	10000	13880 (39%)	14080 (41%)	14350 (44%)	13920 (39%)
Ravi	27270	30000 (10%)	30300 (11%)	30910 (13%)	30300 (11%)
Beas	9370	12320 (31%)	12210 (30%)	12530 (34%)	12530 (34%)
Satluj	75740	112350 (48%)	111320 (47%)	120880 (60%)	116760 (54%)
Total	7380	10050 (-53%)	9710 (-59%)	10230 (-55%)	9720 (-71%)

the late period under pressure from rapid population growth (Table 3.3). The application of the APC index in Table 3.3 illustrates that the upper Indus basin as a whole is projected to drop from a 'no water stress' situation in the refence period to a 'low water stress' situation in the mid period of both scenarios. However, the per capita water availability change is highly heterogenous between the sub-basins. In the reference period the relatively densely populated and transboundary Kabul and Jhelum sub-basins fall into the 'low water stress' category of the APC index and are projected to move into the 'high-' and 'moderate' water stress categories in the late period of the SSP3 scenario, largely due to rapid population growth surrounding major urban centres in the Afghani and Indian shares of the respective basins (Smolenaars et al., 2021). In contrast, other sub-basins, such as Satluj, Chenab and Ravi, all located largely in India, remain firmly in the 'no water stress' category and even face a net increase in per capita water availability in the SSP1 scenario due to the positive effect of climate change on discharges here.

Figure 3.4B demonstrates that during the refence period the consumed share of total annual surface water resources is negligible at about 2%. Because of the seasonal discharge patterns the consumption in the driest (winter) period of the year does exceed 10% of total discharge (Figure 3.4A). Despite rapid population growth the share of total annual water resources consumed in the upper Indus basin only increases to 4.1% and 5.5% in SSP1 and SSP3 respectively in the late period (see Appendix Figure B1). However, the basin-level consumed fraction on average reaches a considerable 15% (SSP1) and 18% (SSP3) over the entire dry season and exceeds 30% during the December and January months. Corresponding to the pace of population growth, the development of relative water consumption differs between sub-basins. In the Kabul sub-basin consumptive needs during the late period in the driest months of the year exceed 80% of available surface water on average and even fully surpass it in low discharge years. In the SSP3 scenarios the consumed share during the wet season also reaches a considerable 17% to 21% (SSP1 and SSP3 respectively). Similarly, in the Jhelum sub-basin the average consumed share over the entire dry season reaches 18% (SSP1) and 23% (SSP3) in the late period and consumptive needs during the winter months may exceed discharges in the driest years. Sub-basins with positive discharge changes due to climate change and low population growth, such as Satluj, remain virtually unaffected in both scenarios.

The rapid increase in consumptive water needs relative to water availability during the dry season is projected to affect environmental flows in the Kabul and Jhelum upper Indus sub-basins. Figure 3.5 illustrates that in these basins by 2080 environmental flows are on average not met for roughly half- (Kabul) and a third of the year (Jhelum). Environmental flows appear to also gradually be affected in the Chenab and Beas sub-basins during low discharge years. On the other hand, environmental flows in the Satluj and main Indus sub-basins see very limited impact in the present and will remain largely unaffected over the course of the century. In some scenarios and timestep, the impact even decreases compared to the present. This is especially true in the Satluj sub-basin, where the increase in flow due to climate change is far larger than the increase in water consumption due to socio-economic changes (see Table 3.2). Environmental flows are least affected during the monsoon season.

3.3.3. Future downstream water availability under socio-economic and climate change

The influence of upper-Indus consumption on the per capita water availability in the lower Indus basin (see Appendix Figure B4) varies greatly between the seasons. Analogous to the periods of the year in which the consumed share in the upper Indus is highest, Figure 3.6

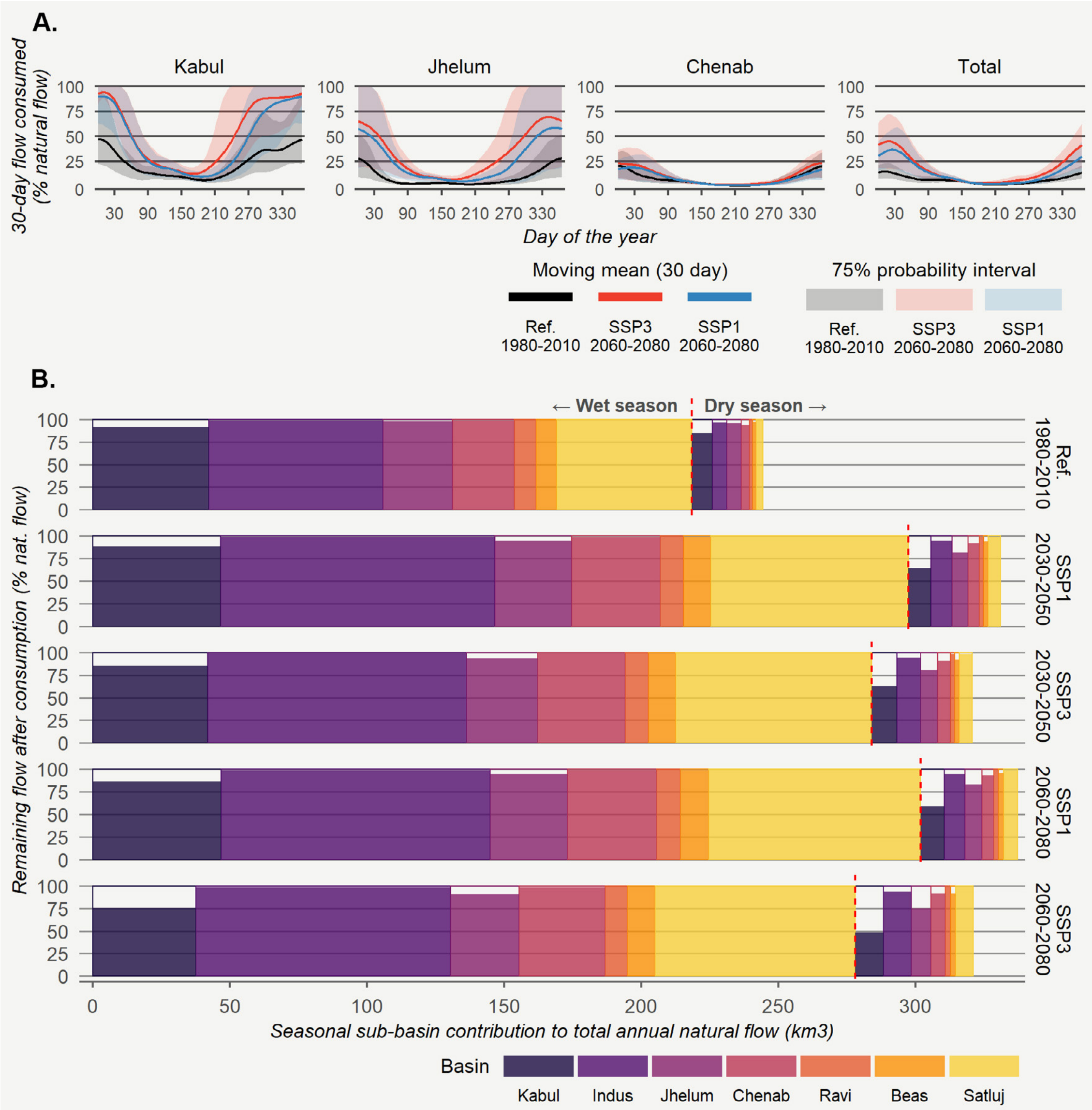


Figure 3.4: Daily share of natural flow consumed in upper Indus sub-basins during the reference period and the projected late time periods (A.). Development of ensemble mean absolute upper Indus outflow under climate change and the impact of consumption (B.).

illustrates that its impact on downstream water availability is most pronounced in the winter season. During the reference period some sub-basins in the Pakistani Punjab are already shown to be slightly affected in the order of 8% to 12%, but in the late period the available water here may reduce by more than a quarter on average. However, the impact during the post-monsoon season demonstrates the most considerable rise. Several Pakistani sub-basins shift from being largely unaffected during the reference period to facing mean water availability reductions of 14% (SSP1) and 20% (SSP3) in the late period.

The influence on water availability during the monsoon season doubles in most basins, but nevertheless does not exceed 6%. Throughout all seasons the impact of upper Indus consumption is strongest in the sub-basins that receive their water from the Kabul and Jhelum upper Indus sub-basins. Additionally, sub-basins with limited local per capita water availability (e.g. due to high population densities or extremely arid conditions) will be more affected, as their relative dependency on mountain water resources is higher. The regional urbanization trend and subsequent spatial concentration of population magnifies this effect in several sub-basins containing large cities. The pattern of basins most affected by upstream consumption is similar between the scenarios, but the degree of impact is higher in the SSP3 scenario.

The impact of upper Indus consumption on lower Indus water availability is not an isolated process, but intertwined with climate changes and with socio-economic changes in the lower Indus itself. Table 3.2 and Figure 3.4B demonstrated that climate change causes an increase in discharge from the upper Indus basin and for the lower Indus a slight increase in precipitation is also projected(Lutz et al., 2019). The isolated impact of climate change (Figure 3.7) likewise increases late period per capita water availability in most lower Indus sub-basins by 20% to 50% compared to reference period climatic conditions. In the areas downstream from the Beas and Satluj upstream sub-basins, largely located in the Indian Punjab and Haryana states, this increase may even exceed 50%. The increase in downstream water availability from climate change outweighs the decrease due to upper Indus water use, except in the sub-basins in Pakistan that are directly downstream from the Kabul and Jhelum sub-basins during the dry season in SSP1. Figure 3.7 moreover demonstrates that lower Indus population growth from an average of 168 million inhabitants over the reference period to 267 million in the SSP1 late period (see Appendix Figure B2) cause a 20% to 50% decrease in per capita water availability of most sub-basins. Rapid population growth to 443 million inhabitants in the SSP3 scenario drives an almost universal decrease of over 60%.

Accordingly, the combined impact of climate change and socio-economic development in the upper Indus largely results in a net increase in the absolute water available to lower Indus sub-basins. However, population growth in the lower Indus basin also requires these resources to be shared among more recipients. The absolute dependency of the lower Indus basin on water resources originating in the upper Indus basin thereby increases. The integrated effect of these processes drives the mean per capita water availability for the majority of lower Indus sub-basins in the SSP1 late period to reduce by 10% to 40% compared to reference period availability, with only the sub-basins in the Indian share of the basin, downstream from the Beas sub-basin, showing slight increase (see Figure 3.7). In SSP3 the integrated drivers cause a general reduction between 40% to 60%. The double sided negative effects of socio-economic development on lower Indus water availability thus outpace the positive effect of climate change.

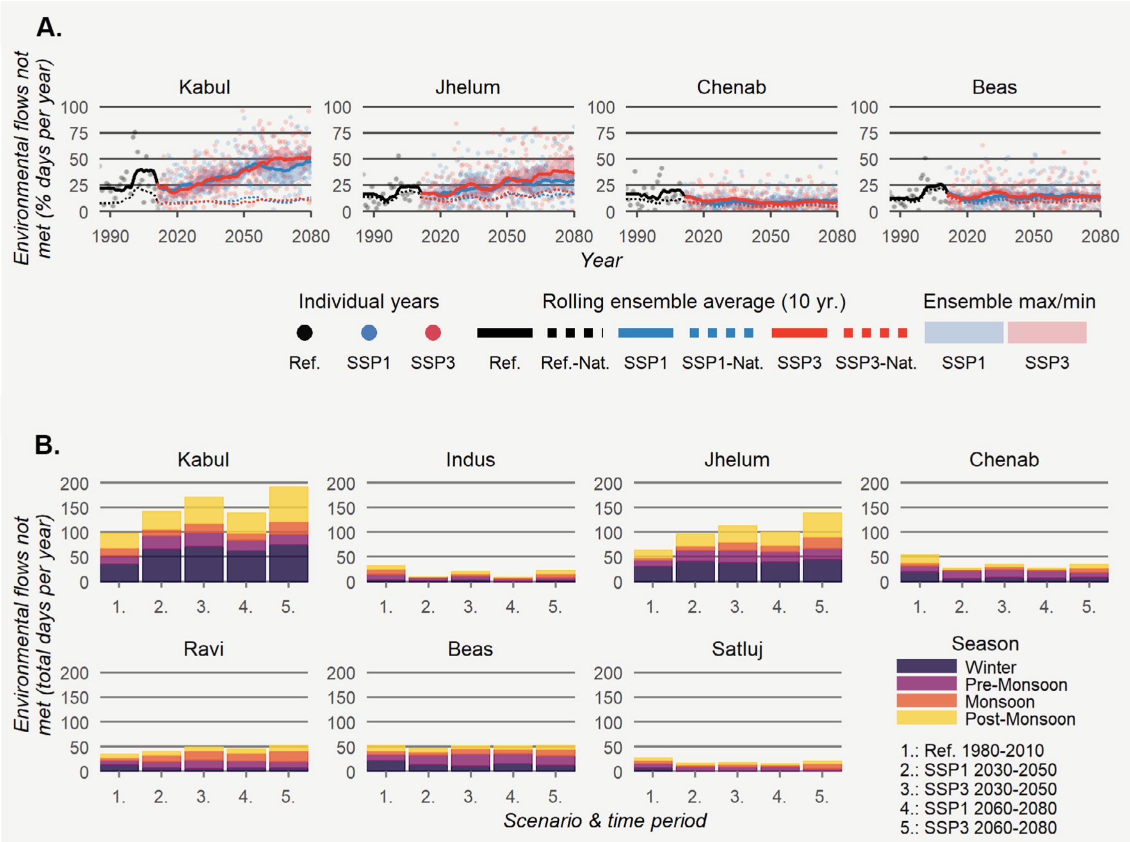


Figure 3.5: Impact of upper Indus consumption on environmental flows at the outlet of the upper Indus sub basins over the assessment period (A.) and per season (B.).

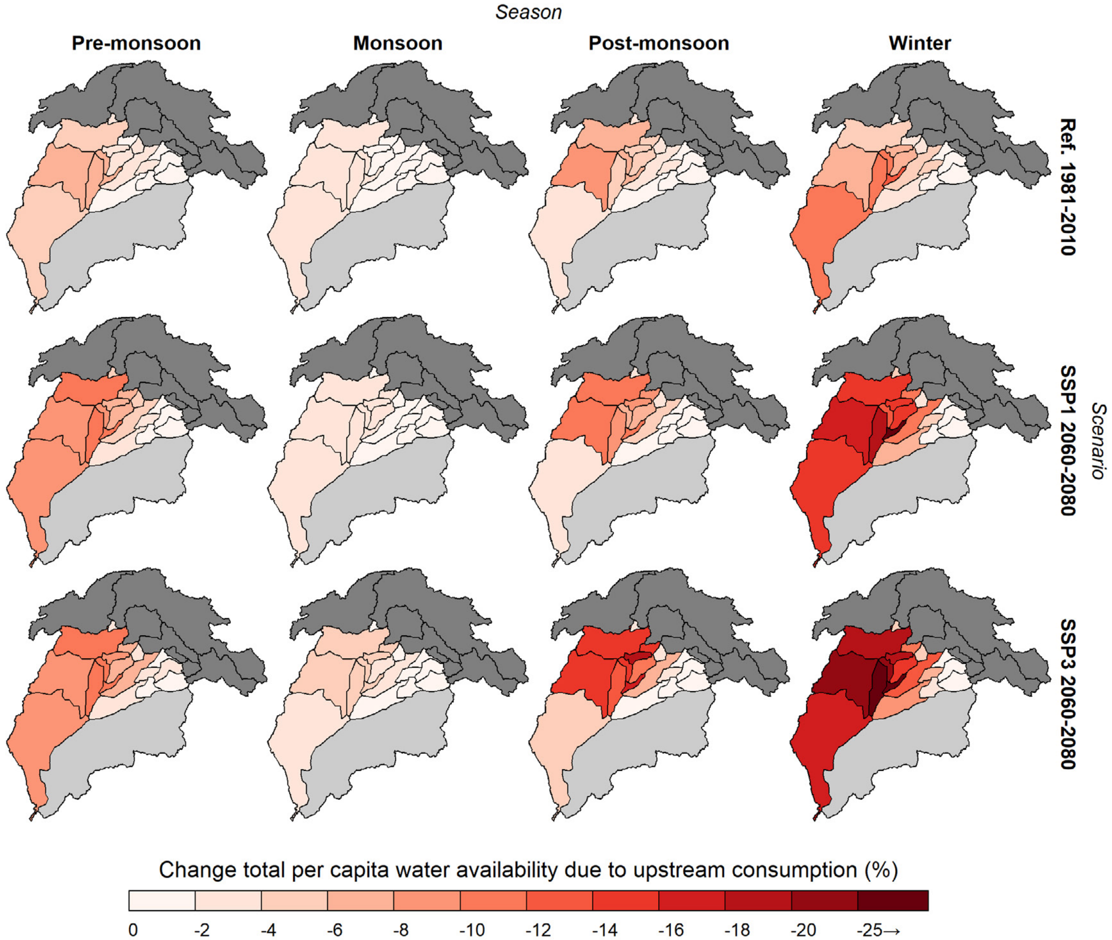


Figure 3.6: Seasonal mean impact of upper Indus water consumption on the water availability per capita of the lower Indus sub basins for all years and ensemble members. The dark grey area herein represents the upper Indus sub-basins. The light grey area is not downstream of any of the upper Indus sub-basins and is therefore omitted.

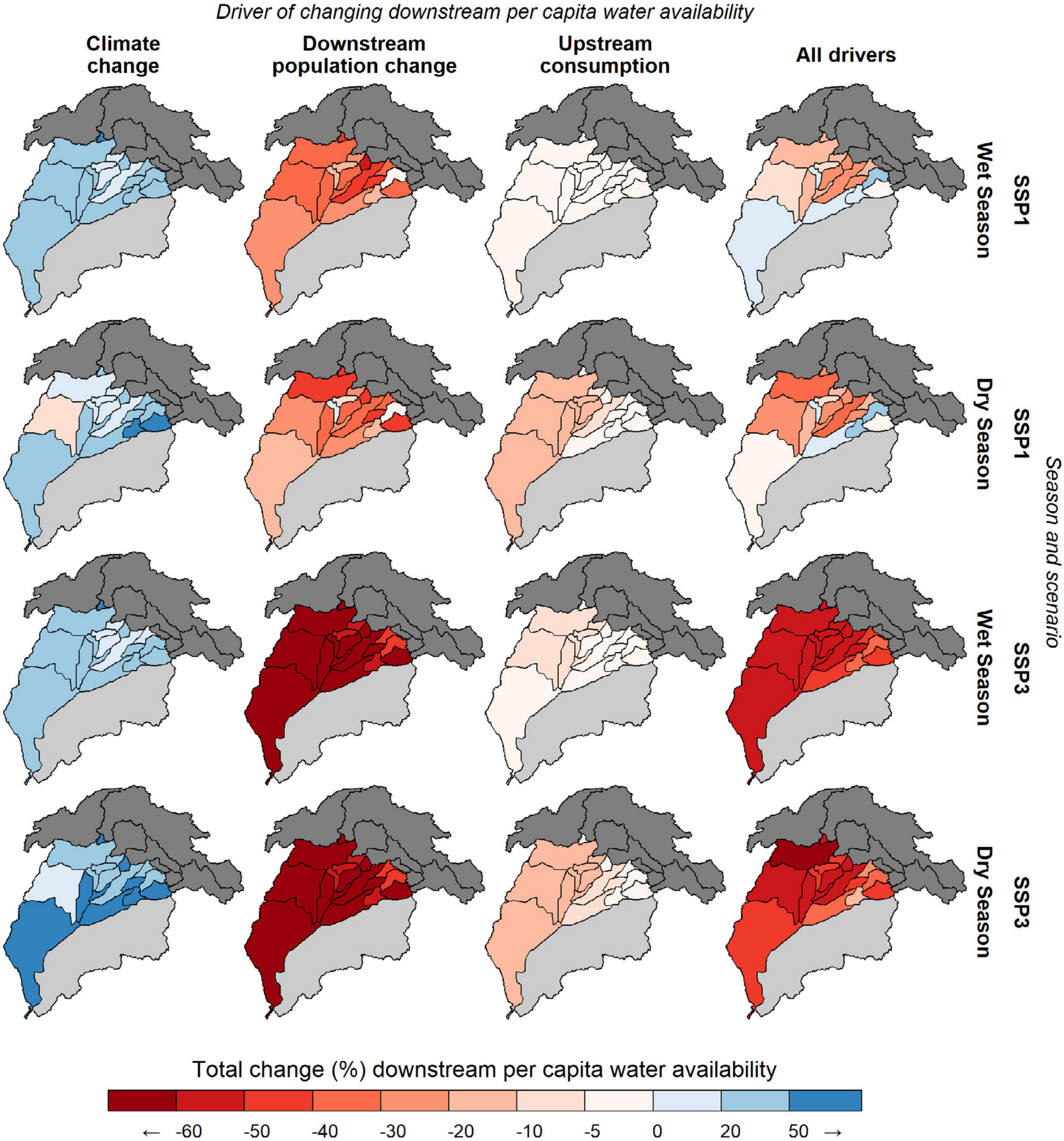


Figure 3.7: Isolated impact of climate change, downstream population change and upstream consumption on seasonal lower Indus water availability in the late period (i.e. compared to late period situation without the effect of the respective driver). Additionally the change in late period water availability with all drivers considered, compared to reference period water availability.

3.4. Discussion

3.4.1. Limitations and opportunities for future research

This study quantified the development of water consumption in the upper Indus basin and its effect on water availability in the lower Indus basin. The water accounting approach that was applied to obtain these results by design is a simplified conceptual representation of the complex Indus basin water system, as this allowed the broader patterns of upstream-downstream dependencies to be assessed. The methodological approach influenced the quantifications presented in this study and their implications.

Primarily, upper Indus consumption was assumed to be fulfilled exclusively with surface water resources generated seasonally within the sub-basins. In reality, there may be spatial mismatches or quality related preference that cause part of upper Indus water demands to be fulfilled by unsustainable groundwater extractions. Groundwater reservoirs may moreover perform a modulating role between seasons, with excess surface water resources infiltrating in wet periods to be used in times when water is scarce. Around the city of Kabul groundwater levels have however dropped considerably over the last decades(Mack et al., 2013). Similarly, on the lower Indus plains, groundwater resources are an important supplementary source for urban and agricultural water demand(Basharat et al., 2015; Biemans et al., 2019a; Wijngaard et al., 2018).But these resources are also depleting rapidly, especially in the Indian Punjab (Richey et al., 2015; Salam et al., 2020). The impact of upper Indus basin water consumption on water availability in the lower Indus in the dry season will remain subdued while these resources are still available. This does however imply that groundwater dependency, and thereby overextractions, are likely to aggravate. Due to a lack of spatial coverage in observational data, the availability and long-term durability of groundwater resources in the upper Indus basin remain uncertain(Cheema et al., 2014; Qureshi et al., 2010; Salam et al., 2020). More research into the status and development of groundwater here is required so that it may be considered in future research steps.

Water quality issues can similarly play an important role in upstream-downstream relations(Wolf, 2007), as exemplified by transboundary water quality disputes emerging in the Chenab and Jhelum sub-basins(Ahmad & Iqbal, 2016; Zawahri & Michel, 2018). Return flows from domestic, industrial and agricultural water usage upstream may be polluted and reduce the downstream availability of water that is of usable quality(Yoon et al., 2015). However, water stress and availability in our analysis are operationalized using indicators for water quantity and do not consider the impact of reduced water quality. The water stress experienced in the lower Indus due to expanding upstream activities may hence be higher than the reduction in availability projected in this study, if pollution prevention measures are not taken. Follow-up research could expand the water accounting analysis applied in this research with water quality indicators for a more holistic assessment of future upstream-downstream linkages. Such analysis may additionally reflect on increasing pollutions with socio-economic development and the need for pollution prevention measures to curb water stress.

In our upstream-to-downstream allocation routine, we moreover assumed upstream outflows to be distributed equitably over all downstream inhabitants. Water use activities in the lower Indus sub-basins were thereby not considered. However, inhabitants closer to upper Indus sub-basins may consume more upstream water than their allocated share and reduce water availability further downstream. Other lower Indus sub-basins with surplus local water resources may positively affect water availability in other sub-basins. On the other hand, intra-national water sharing treaties, such as the Pakistani Water Appointment Accord, do ensure that upstream water distribution throughout the lower Indus basin is not determined solely on the independent self-interest of each downstream region(Hassan et al., 2019). The results of this study thus provide quantified insight into general trend of lower Indus water availability and the times and areas most likely to be affected by changing upper Indus water use activities from an intrinsic upstream-to-downstream perspective, instead of fully disaggregated quantifications of future water distribution in the lower Indus basin.

High-resolution spatial information on the development of water resources is however required to support data-driven water management and adaptation policy making to support the SDGs(Laghari et al., 2012; Rangecroft et al., 2019; Yillia, 2016). Our assessment made considerable gains in this regards compared to previous upstream-downstream studies, but further spatial disaggregation with fully distributed models and the subsequent inclusion of adaptation measures to curb water stress are important follow-up steps for robust adaptation planning. Accounting for the unique regional, often socio-economic, characteristics that govern water distribution in transboundary rivers basins is challenging in data-intensive and process-based hydrological models. In this light, our conceptual approach offers a valuable alternative to establish initial benchmarks. Our accounting routine provides disaggregated insight into potential hotspot areas and seasons for upstream-downstream impacts and its drivers, with only limited data requirements and a flexible and transparent water allocation mechanism. This approach could similarly be applied to study future upstream-downstream linkages in other complex transboundary basins such as the Mekong and the Nile(Johnston & Smakhtin, 2014). Follow-up research could additionally perform a similar assessment to quantify hydrological interactions between sub-basins within the lower Indus. The relation between the irrigation-dominated plains of the Indus midstream and the hyper-arid delta could be of particular interest(Laghari et al., 2012). Similarly, more insight into the interplay between socio-economic and climatic drivers for future upstream-downstream linkages in the Indus basin is important, for example by using different, less conventional, RCP-SSP scenario combinations.

3.4.2. Implications for future transboundary water management and adaptation planning

The quantifications presented here provide valuable initial insight into the increasing relevance of water use activities in the upper Indus for the basin's upstream-downstream linkages and hydro-politics. Consistent with other studies(Vinca et al., 2020; Viviroli et al., 2020; Wijngaard et al., 2018), per capita water availability in the lower Indus was shown to decrease over the projected period under integrated climatic and socio-economic changes, while the dependency on upstream water resources increases. Within this development, the reduction in average annual lower Indus water availability, that can be contributed to expanding water consumption in the upper Indus, remains limited between 4% and 5%. This is in a similar range to study outcomes by Munia et al. (2016) and Degefu et al. (2019), who found current upper Indus consumption to increase downstream water stress by respectively 2% to 4% and 1% to 5%.

However, our results also demonstrate that, when using a spatio-temporally disaggregated approach, hotspot seasons and sub-basins emerge in the lower Indus where the reduction in water availability due to upstream consumption can exceed 25%. Most affected hereby are the densely populated and rapidly urbanizing central Indus plains of Pakistan, downstream of the Jhelum and Kabul sub-basins, during the dry winter season. The upstream areas and water use activities of these sub-basins are located in the Afghani and Indian shares of the basin respectively. The disaggregation of water availability drivers additionally demonstrated that these upstream changes compound a larger decrease in downstream per capita water availability due to population growth, especially in sub-basins with major cities. This suggests that growing upstream consumption will considerably contribute to increasing transboundary water stress in the lower Indus in the dry period of the year in which pressure on water resources is already highest (Wijngaard et al., 2018). Systemic adaptive changes to the irrigation-dominated lower Indus water system, as proposed by previous studies (Immerzeel & Bierkens, 2012; Immerzeel et al., 2020; Vinca et al., 2020; Wada et al., 2019), are thus needed to ensure long-term downstream water security here. Our study highlights however that these efforts, and modelling studies in support of them, must explicitly account for changing upper Indus water use and its implications for water availability downstream.

This study furthermore provides novel insight into the future water balance of upper Indus sub-basins. Strong population growth around the largest urban centres of the upper Indus was demonstrated to cause the Jhelum and Kabul sub-basins to become water stressed themselves by the second half of the century. During the low-flow winter season consumptive water requirements here will consistently claim the majority of available surface water. The actual water demands required to satisfy consumptive requirements are manifold higher (Bijl et al., 2016) and can likely structurally not be met. This indicates that adaptive changes to regional water management and water use behaviour are essential to mitigate water scarcity issues and achieve water security SDGs, not only in downstream Pakistan, but in the Indian and Afghani shares of these upstream sub-basins as well. During the wettest period of the year over 90% of surface water remains available. A valuable adaptation avenue suggested by Amin et al. (2018) may therefore lay with modulating seasonal difference with storage dams specifically for upper Indus water provision.

However, the Kabul and Jhelum are transboundary sub-basins. Past plans to construct additional hydropower dams, with limited storage capacity, in the Indian share of the Chenab sub-basin have led to disputes over fears that this infrastructure could be used to further control the flow of vital dry season water resources to downstream Pakistan and infringe on the terms of the Indus Water Treaty (Ahmad & Iqbal, 2016). Both the increasing upstream water use projected for these sub-basins, and hydrological interventions to facilitate this use such as storage dams and diversion canals, may therefore intensify upstream-downstream water competition and aggravate existing hydro-political tensions between the riparian states (Atef et al., 2019; Gupta & Ebrahim, 2017). Transboundary water competition may further exacerbate as downstream demands in the heavily irrigated and densely populated Pakistani and Indian Punjab are also expected to increase with substantial projected population growth, particularly in the SSP3-RCP8.5 scenario (Wijngaard et al., 2018). This demand is most likely to be met with increased use of upstream water and may prompt riparian states to capitalize to even greater extent on upper Indus water resources allotted to them in the Indus Water Treaty (Zawahri & Michel, 2018).

The results of this study therefore support the claims of previous studies that the Indus Water Treaty needs to be revisited (Ahmad & Iqbal, 2016; Kalair et al., 2019; Qamar et al., 2019; Wada et al., 2019) and include the Kabul tributary, and thereby Afghanistan (Zawahri & Michel, 2018), to ensure equitable and sustainable future water allocation between riparian states and provide a robust platform for the development of basin-wide adaptation strategies. The role of climatic changes in this process has been at the forefront of scientific attention (Kalair et al., 2019; Qamar et al., 2019) and policy making (Parvaiz, 2021) in recent years. However, our quantifications show that socio-economic changes may have a larger influence on future upstream-downstream linkages in the basin and the subsequent water stress experienced by its inhabitants. This suggests that any revisitation of existing treaties, like the IWT, towards improved shared water management must account for future socio-economic changes in both the upper and lower Indus basin, alongside the role of climatic change. We specifically identified several transboundary interactions that are likely to intensify in the future and must be addressed accordingly in this process. These hotspots moreover provide targets of special consideration for transboundary cooperation, adaptation policy making and future hydrological modelling studies in support of the integrated pursuit of water and food security SDGs.

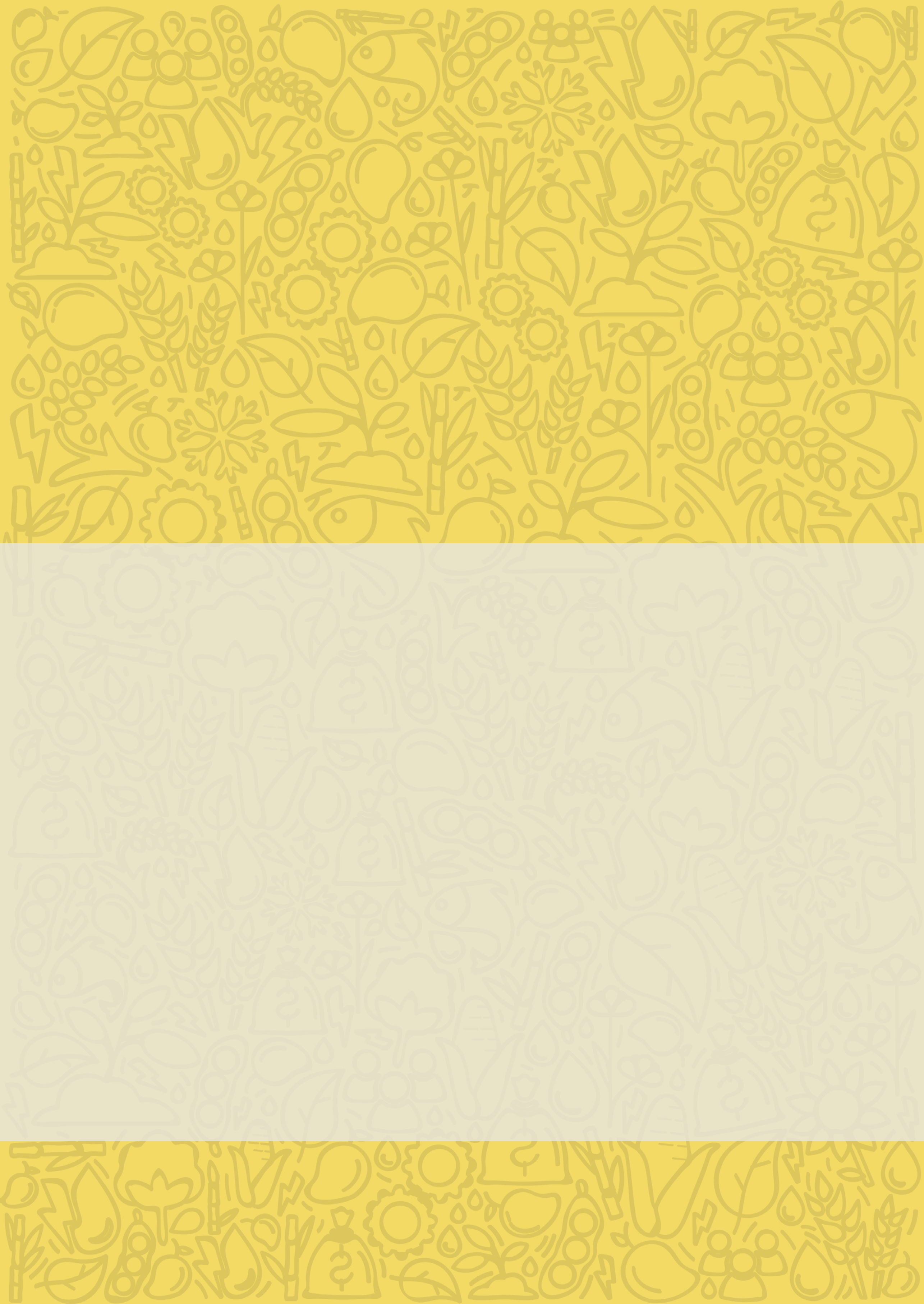
3.5. Conclusions

This study quantified the role of current and future water use in the upper Indus on downstream water availability for two integrated socio-economic development and climate change scenarios. The results demonstrate that growing water usage in the upper Indus basin is a significant factor in the evolving upstream-downstream linkages of the Indus basin. The combined consumption across the seven upper Indus sub-basins is projected to increase from 6.9 km^3 yr^{-1} presently to 13-17km^3 yr^{-1} by 2060-2080. This causes considerable pressure on surface water resources in the dry season. The transboundary Kabul sub-basin, shared by Afghanistan and Pakistan, and the Jhelum sub-basin, shared by India and Pakistan, in particular are demonstrated to become increasingly water stressed due to rapid population growth, despite an increase in surface water availability through climate change. Water requirements during the critical winter months here may structurally exceed 50% (Jhelum) and 90% (Kabul) of surface water availability in the future and increasingly impede environmental flows from being met. Scarcely populated upstream sub-basins, such as Satluj and Ravi in the Indian share of the basin, instead see the effects of climate change come out ahead and face an overall increase in future water availability.

The large differences in relative upper Indus water consumption between seasons and sub-basins result in spatiotemporal impact hotspots in the lower Indus where surface water availability is reduced by over 25% compared to natural flow conditions. This amplifies a greater decrease in future downstream per capita water availability due to population growth. The negative impact of these two socio-economic drivers outweighs the positive effects of climate change on water availability, especially under the rapid population growth of the SSP3-RCP8.5 scenario. Growing upper Indus water consumption particularly plays a substantial role in the decreasing trend of dry season water availability of the densely populated Indus plains of in the Pakistani share of the basin. Expanding water usage in the upper Indus may thus lead to *in situ* water scarcity issues in several upstream sub-basins and intensify the already considerable water stress faced in transboundary downstream areas during the dry season.

The quantified outlook on the development of upstream-downstream linkages under various drivers provided in this study holds several insights for transboundary cooperation, long-term water management and adaptation planning in the hydro-politically complex Indus basin. Foremost, adaptation strategies towards achieving the interlinked water and food security SDGs are required not just in lower Indus plains of Pakistan, but also for the Kabul and Jhelum sub-basins of the upper Indus that are administered largely by Afghanistan and India. This implies that adaptation policy and revisions of shared water management practices must explicitly consider for the impact of socio-economic changes on the evolution of upstream-downstream dependencies in the Indus basin and its transboundary implications for water demand and availability throughout it. Future disaggregated modelling assessment of the future Indus basin water system in support of these processes similarly need to include socio-economic development in the upper Indus. Subsequent research may focus on further untangling Indus upstream-downstream linkages by disaggregating hydrological dependencies within the lower Indus as well, and by evaluating implications by-and-for adaptation strategies.

Acknowledgements
Work of all the authors is supported by the SustaIndus project funded by NWO Wotro (Project W 07.30318.002), the Interdisciplinary Research and Education Fund (INREF) of Wageningen University and Research, and Utrecht University. HB would like to acknowledge partial funding from the Wageningen University & Research "Food Security and Valuing Water programme" that is supported by the Dutch Ministry of Agriculture, Nature and Food Security". SD acknowledges partially support by Sustainable Development Investment Portfolio (SDIP), the Department of Foreign Affairs and Trade (DFAT), Government of Australia, the Swiss Agency for Development and Cooperation (SDC) and by core funds from ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland and the United Kingdom. The views and interpretations in this publication are those of the authors, and they are not necessarily attributable to their organizations.



4. Agricultural System Development

Exploring the potential of agricultural system change for future water and food security adaptation in the Indus basin

Water and food security in the Indus basin are highly interlinked and subject to severe stresses. Irrigation water demands presently already exceed what the basin can sustainably provide, but per capita food availability remains limited. Rapid population growth and climate change are projected to further intensify pressure on this water-food interdependency. The agricultural system of the Indus basin must therefore change and adapt to be able to achieve the Sustainable Development Goals (SDGs) for water and food security. The development of robust policies to guide such changes requires a thorough understanding of synergies and trade-offs between water and food security that agricultural transitions may hold. In this study, we defined three trajectories for agricultural system change that represent different prioritizations between water and food security. We assessed these changes with a high resolution modelling framework for two scenarios of climatic and socio-economic change over the period 1980-2080. Our results demonstrate that agricultural system change can maintain sufficient per capita food production under population growth, but that such changes may strongly aggravate water stress. Conversely, a shift to sustainable water management means basin-level food self-sufficiency cannot be achieved. This suggests that biophysical limits likely exist that prevent agricultural system changes to ensure both sufficient food production and improve water security in the Indus basin, especially under strong population growth. Our study concludes that agricultural system changes are an important adaptation mechanism towards achieving water and food SDGs, but must be developed alongside other strategies that can mitigate its adverse trade-offs.

Published as: Smolenaars, W.J., Jamil, M.K., Dhaubanjar, S., Lutz, A.F., Immerzeel, W.W., Ludwig, F., Biemans, H. (2023). "Exploring the potential of agricultural system change as an integrated adaptation strategy for water and food security in the Indus basin." Environment, Development and Sustainability, 1-36.

4.1. Introduction

Water and food security are strongly interlinked for the over 260 million inhabitants of the Indus basin (Kirby et al., 2017). The hydrology of the basin is strongly modified by massive water extractions and water transfers in support of one of the largest contiguous irrigation systems in the world. This system is crucial for regional food production, but also has a strong effect on the availability of water throughout the basin, especially in the areas surrounding the irrigation network and in regions further downstream during the dry season (Basharat et al., 2014). Conversely, relatively small changes in the timing or amount of water supply to the agricultural system can have a large effect on yield and, by extension, on regional food security (Rasul, 2014). This delicate water-food interdependency has become increasingly disbalanced. Irrigation water demands to sustain the steadily expanding agricultural system exceed surface water availability during the dry season and have driven a considerable share of irrigation water to be sourced from groundwater(Biemans et al., 2019b). Such irrigation practices are unsustainable on the long-term, as groundwater resources in many places of the basin are over-extracted (Cheema et al., 2014; Salam et al., 2020). Groundwater is in addition often brackish, leading to soil salinization (Salam et al., 2020). Furthermore, the enormous surface water extractions for food production cause environmental flows in the unique ecosystem of the Indus delta to not be met for large parts of the year (Laghari et al., 2012).

The current interdependencies between water and food security, and corresponding trade-offs, are likely to intensify in the future (Rasul, 2014). Foremost, the basin is projected to face rapid economic development and population growth (Wada et al., 2019). The demand for food will consequently increase rapidly (Smolenaars et al., 2021). Self-sufficiency for staple crops, such as wheat, is an important policy goal for the riparian states (Bishwajit et al., 2013). The agricultural system of the Indus plains, regarded as the breadbasket of both Pakistan and India, will therefore likely face pressure to further expand and intensify food production (Vinca et al., 2020). Food production on the hot and arid plains may however be severely affected by increasingly harsh climatic conditions and more erratic water availability and precipitation patterns (Tariq et al., 2014). At the same time, the demand for water faces even steeper growth, especially for urban uses (Smolenaars et al., 2022; Wijngaard et al., 2018). The intersectoral competition over dwindling surface water resources, which are presently dominated by use for irrigation, will therefore aggravate (Laghari et al., 2012). This competition may drive further groundwater overuse (Lutz et al., 2022). Sustainable Development Goals (SDGs) for water (SDG 6) and food (SDG 2) security, but also those related to riverine ecosystem health (SDG 15), are therefore unlikely to be met unless integrated adaptation action is undertaken to peaceably reallocate water resources across competing players (Immerzeel et al., 2020).

The main interface for water and food in the Indus basin is the agricultural system, in particular through its land-use, and crop and water management practices (Wijngaard et al., 2018). The present and future properties of agricultural land-use and management practices here are shaped considerably by policy decisions (Singh & Park, 2018). The combination of being strategically important for both water and food, and partly steerable, designates agricultural change and development as an important component of integrated adaptation strategies that aim to reconcile water and food security (Fathian et al., 2023; Ostad-Ali-Askari et al., 2017; Wada et al., 2019). The agricultural system must therefore evolve to manage the new challenges and priorities, imposed by climatic, economic and demographic changes, on both water management and food production. Yet, this interplay also demonstrates that the future trajectory of agriculture in the Indus basin is complex. Rather than a fully autonomous process that can be 'predicted', the development of the agricultural system is a continuous product of evolving societal choices within hard biophysical constraints throughout the basin (Farah et al., 2019). Policy-making to guide this process in a sustainable direction therefore requires spatially explicit insight into the consequences of a range of alternative agricultural system futures that convey different visions for its position in the Indus water-food nexus (Biemans & Siderius, 2019). The integrated exploration of multiple future scenarios allows robust agricultural strategies to be identified for adaptation planning and for maladaptive trajectories to be avoided.

Most of the existing modelling research on future interactions between water and food security in the Indus basin has however assumed that future agricultural developments will follow a similar pattern to historical developments (Lutz et al., 2022; Vinca et al., 2020). In addition, several other studies did not account for any type of change in future land-use or crop choices (Droppers et al., 2022; Wijngaard et al., 2018; Yang et al., 2016). This suggests that there is a lack of quantitative information regarding the potential benefits and drawbacks of agricultural development strategies, other than a continuation of current practices, for adaptation policy making in the basin. In this study, we therefore used a modelling approach to explore how multiple alternative strategies for agricultural development may affect water-food interactions in the Indus basin under climatic and socio-economic changes. *The aim of this study is accordingly to assess what may happen to water and food security 'if' certain strategies for agricultural system change are adopted*. Hence, we explicitly do not attempt to forecast the future impact that agricultural changes may have on the water system of the Indus basin, but instead base our analysis on hypothetical 'what-if' premises. To do so, we first established three agricultural development narratives that represent different positions in the policy space between water and food security (i.e. priority on food, on water, or a balance). The narratives were then studied with a fully distributed crop-hydrology modelling framework under socio-economic and climate change.

The results of this study allow for novel insights into the impact of multiple contrasting directions for agricultural development, and corresponding strategic policy choices, on both future water and food security. This type of insight is presented both at high spatial resolution, and aggregated at the basin level in relation to other important regional developments such as climate change and population growth. The information provided by these study outcomes is important for adaptation policy-making in the Indus basin as it supports a better understanding of the potential benefits and limitations of agricultural system changes as an adaptation mechanism to reconcile and achieve SDG2 and SDG6.

4.2. Materials and Methods

We conducted a scenario analysis, based on the SSP-RCP framework over the period 1950-2080, using a spatially distributed crop-hydrology model. Our methodological approach consisted of five steps:

1. First, we defined two regionally downscaled SSP-RCP forcing scenarios that provide a broad storyline for the development of population, economic, climatological and technological factors.
2. We developed three unique narratives for the future of the Indus agricultural system and embedded these within the downscaled SSP-RCP scenarios. This process defined

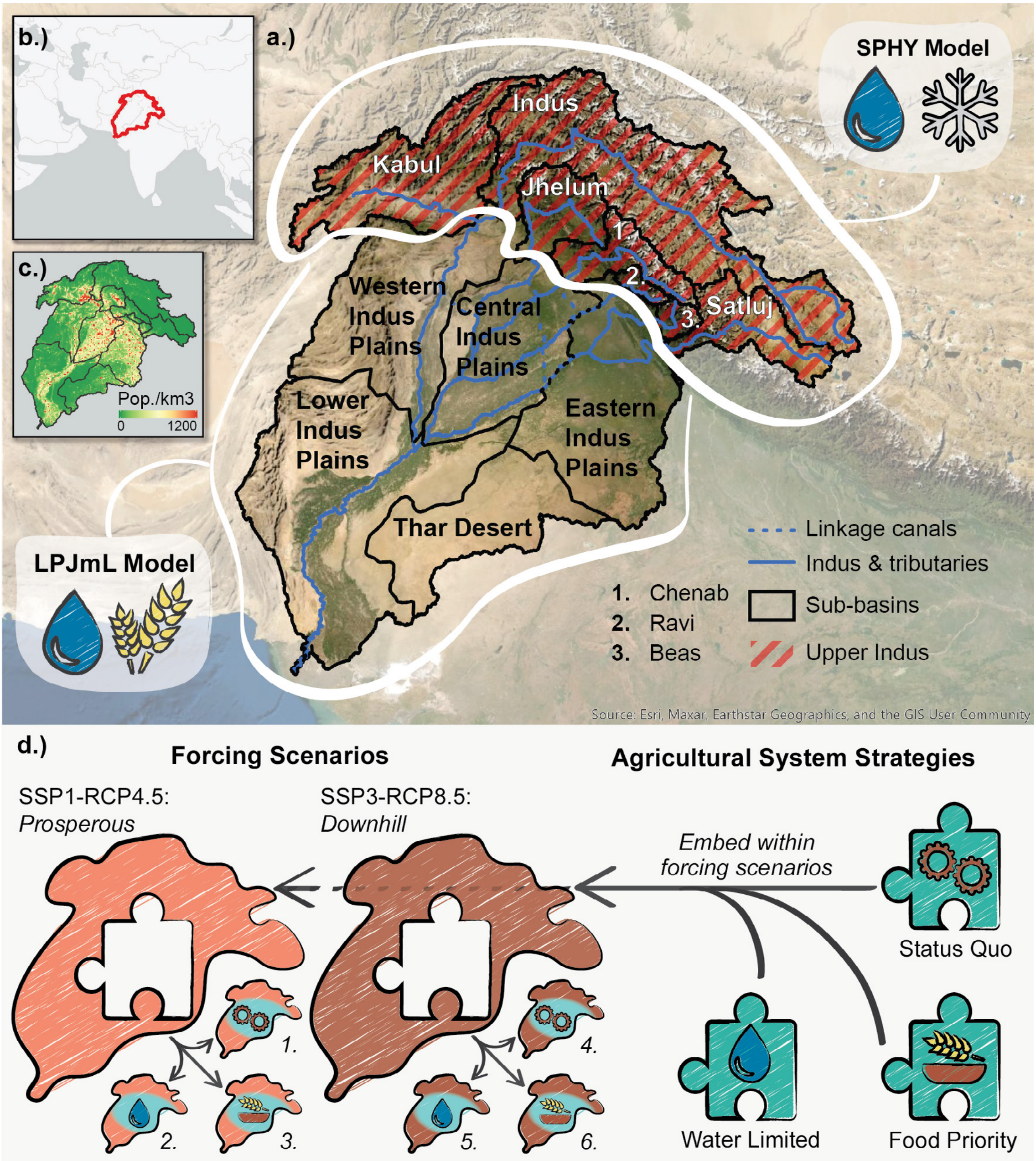


Figure 4.1: Geography of the Indus basin with sub-basin delineation and applied models (a.) with insets for the location of the basin in the wider region (b.) and the 2010 population (c.) density (Klein Goldewijk et al., 2011). In addition the conceptual representation of how agricultural development narratives are embedded within forcing scenarios to create the agricultural development strategies used in this study (d.).

six internally consistent strategies for agricultural development in the Indus basin. An overview of the strategies can be found in Table 4.1.

3. Next, we quantified and spatialized the land-use change component of the agricultural development strategies at annual timesteps over the period 1950-2080 and at 5 arcmins resolution. This was done using observational statistics of historical crop production and yields at the state/provincial level for India and Pakistan from 1952 to 2015, in combination with a spatial dataset of crop distributions. We did this for both the Rabi (dry) and Kharif (wet) cropping seasons.
4. We used the spatial land-use projections and other strategy elements as input data for the fully distributed LPJmL crop-hydrology model. Besides land-use change, we also accounted in our model runs for yield gap closure, water management, climate change, and for changes in the water use of the domestic and industrial sectors as a result of socio-economic developments.
5. Lastly, we analyzed the spatial outputs of the model to determine how agricultural system changes affect water and food security in the future and how these impacts may interact with other changes in the basin.

4.2.1. Forcing scenarios

The contextual core of our scenario analysis is determined by two integrated downscaled forcing scenarios from Smolenaars et al. (2021). These scenarios are regionalized versions of the SSP-RCP (Shared Socio-Economic Pathways & Representative Concentration Pathways) framework specifically for the Indus basin. We used the optimistic Prosperous (SSP1-RCP4.5, hereafter SSP1) and the pessimistic Downhill (SSP3-RCP8.5 hereafter SSP3) scenarios. For both scenarios, spatially explicit population and economic data was obtained through the scenario-specific datasets published by Smolenaars et al. (2021). Downscaled climate data for RCP4.5 and RCP8.5 was also available, consisting of an ensemble of four downscaled Global Circulation Models (GCMs) for each scenario (Lutz, ter Maat, et al., 2016). These climate models were selected for their performance in representing historical climatic patterns for the Indo-Gangetic plains. This procedure used an envelope approach to ensure that a diverse range of future projections was selected from the available models with good performance. The models were subsequently downscaled and bias corrected to observational climate data for the reference period (1971-2000) to ensure an optimal representation of past, present and future regional climatic patterns. A more elaborate overview of the climate models and projections used in this study can be found in Lutz, ter Maat, et al. (2016).

- SSP1-RCP4.5 Prosperous: the SSP1-RCP4.5 scenario assumes socio-economic development in the Indus basin will follow a sustainable and moderate trajectory. Population growth decreases rapidly, stabilizing by 2050 at approximately 350 million people, but the basin's population is increasingly concentrated in highly developed urban centers. Similarly, economic growth, though steady, is characterized by an emphasis on sustainable development, smart and clean technologies, and the optimized use of resources. There is a balance between different societal needs with considerable emphasis on nature-based practices and improved international collaboration between riparian states. Global climate change is relatively moderate, being limited to the RCP4.5 trajectory.
- SSP3-RCP8.5 Downhill: contrastingly, the SSP3-RCP8.5 scenario assumes an increasingly regionalized Indus basin with considerable socio-economic problems. Population growth continues at its present rapid pace, reaching a population of 450 million by 2050 and over 600 million by 2080. Economic growth, on the other hand, remains limited with large

income disparity and inequality throughout the basins. In this scenario, global climate change is severe, corresponding to an RCP8.5 scenario. The precarious climatic and socio-economic developments drive riparian states to increasingly focus on internal affairs and towards maintaining stability. As a result, land-use, water management, and agricultural development policies are largely focused on internal sufficiency and security, rather than sustainable and mutually beneficial practices at the basin-scale.

4.2.2. Agricultural system strategies

Next, we defined three 'what-if' narratives for the development of the Indus basin agricultural system; *Status Quo*, which continues current patterns, *Water Limited* which sees a radical shift towards sustainable water management, and *Food Priority* which prioritizes a self-sufficient food system. Each narrative reflects a different strategic position for agricultural system development in relation to the active policy discourse on the dependencies between water and food security. The narratives were developed by reviewing scientific literature and national and regional policy documents (Appendix Table C3), followed by the consultation of regional experts and policymakers in Pakistan (Appendix Table C1 and Figure C6). Each narrative consists of characteristics for the following aspects:

- Agricultural land-use: change in cropping intensity (net sown area) and the mix of food and cash crops.
- Water management: change in the ratio of rainfed to irrigated agriculture and the use of groundwater for irrigation.
- Crop management: change in annual yield gap closure (i.e. the production intensity).

To define agricultural development strategies, the narratives were embedded as scenario elements in the SSP-RCP forcing scenarios (Figure 4.2D). The final characteristics of each strategy therefore depend on the agricultural system narratives and on the storyline and constraints of the respective forcing scenario. All strategies moreover share several central constraints:

- Agricultural land in the Indus basin is facing increasing competition from urban areas (Farah et al., 2019; Rasul, 2016). Yet, land-use intensity in large parts of the basin is still relatively low, as a considerable share of arable land is left fallow between years and seasons or is not connected to the irrigation system(Kirby et al., 2017). We therefore assume that the geographical area in use for agriculture will not expand further, but instead must intensify the cropping intensity. The total cropped area thereby stays the same, but the effective net sown area can still increase greatly. In addition, production intensification may occur through year-on-year yield-gap closure. Historical yield-gap closure was estimated as a reference point, using potential yield approximations by Kirby et al. (2017), and historical yield developments from Khan et al. (2021) and subregional agricultural statistics.
- Crops are divided into seven groups. The first groups are formed by the three major food crops of the basin (wheat, rice and maize), and cotton and sugarcane, the two major cash crops (Laghari et al., 2012). These crops together account for over 90% of total net sown area in the basin(Kirby et al., 2017). The sixth group is oilseeds and pulses, crops that used to be an important part of the Indus agricultural system, but that were outcompeted in the last few decades by rice-wheat systems and cash crops (Singh & Park, 2018). The last crop group consists of all other crops, including horticulture.

- In compliance with the timeframe of the SDGs, all strategic agricultural system changes start in 2015 (last common year of statistical data, see Appendix Table C3) and are assumed to be accomplished by 2030.

This produced the following narratives and strategies (see Table 4.1) for agricultural system development:

- *Status Quo: what-if the agricultural system continues to develop as it has done historically?* The first agricultural development narrative that we defined is a *Status Quo* premise, in which agricultural system changes continue alongside their historical and present trajectory. The net sown area of staple food crops is therefore assumed to continue to develop in relation to population (Kirby et al., 2017). Effectively, this means that the rice-wheat system, which over the last decades has become the main cropping system in the Indus basin(Singh & Park, 2018), remains dominant. In the SSP1 scenario, with moderate population growth, cropping intensity is assumed to increase only for rainfed areas to prevent further groundwater over-extraction. In the SSP3 scenario, cropping intensification occurs for both rainfed and irrigated areas, proportional to the current ratio of rainfed and irrigated agriculture of each crop group. The land-use for cash crops sees sugarcane continue to steadily replace cotton (Watto & Mugera, 2015). The net sown area for other crops, oilseed and pulses is assumed to remain static. Lastly, annual yield gap closure continues at its present rate in SSP3 and reduces slightly in the sustainable SSP1 scenario.
- *Water Limited: what-if the agricultural system develops with priority on water conservation?* The second agricultural development narrative, *Water Limited*, assumes that water scarcity forces a break from historical patterns and towards more water-efficient agricultural practices. For food crops, this means that the water-intensive cultivation of rice is diversified towards maize, oilseeds and pulses(Sidhu et al., 2021; Singh & Park, 2018). The ongoing replacement of cotton with water-guzzling sugarcane is halted (Kirby et al., 2017) and then reversed, with cotton overtaking the sugarcane area. Land-use intensification in this strategy is only allowed in rainfed areas. For predominantly irrigated crops, this means no expansion of net sown area is allowed, and can only come at the expense, or the replacement, of other crops. Moreover, in the SSP1 scenario, the overuse of groundwater by the irrigation systems is phased out as it poses great challenges for environmental sustainability(Singh & Park, 2018). Concerns over water quality and soil health similarly demand a more moderate production intensification through the use of agricultural inputs, such as fertilizers (Shahbaz & Boz, 2022). This causes annual yield gap closure to slow down, especially in the sustainability-focused SSP1 scenario.
- *Food Priority: what-if the agricultural system develops with priority on internal food self-sufficiency?* The last agricultural development narrative that we defined is the *Food Priority* strategy. Here, achieving internal food self-sufficiency is the most dominant driving force for the development of agriculture in the region. This scenario prioritizes the allocation of scarce land and water resources towards food production for internal consumption. Continued rapid population growth in the SSP3 scenario therefore demands a rapid growth to full double cropping in irrigated areas (i.e. 200% cropping intensity). In terms of crops, the rice-wheat systems, which provide the two most important staple crops(Singh & Park, 2018), continues to grow in dominance, at the expense of other crop groups. Moreover, the export-based, and non-edible, cotton crop is gradually switched to food crops that are currently imported, such as oilseed and pulses(Kirby et al., 2017). The net sown area of sugarcane in addition increases to reduce sugar imports (Watto & Mugera,

Table 4.1: Overview of land-use and management changes for each of the agricultural development strategies in relation to SSP forcing scenarios.

Strategy elements	Status Quo		Water Limited		Food Priority	
	SSP1	*SSP3*	*SSP1*	*SSP3*	*SSP1*	*SSP3*
Agricultural land-use						
Food crops mix	Same crop mix as present.	Same crop mix as present.	Rice largely replaced by oilseeds, pulses and maize.	Rice largely replaced by oilseeds, pulses and maize.	Rice-wheat systems continue to grow more dominant.	Rice-wheat systems continue to grow more dominant.
Cash crops	Sugarcane gradually replaces cotton	Sugarcane gradually replaces cotton	Sugarcane is rapidly replaced by cotton in the Kharif season, and oilseeds and pulses in the rabi season.	Sugarcane is rapidly replaced by cotton in the Kharif season, and oilseeds and pulses in the rabi season.	Cotton replaced by oilseeds and pulses. Sugarcane continues to expand.	Cotton replaced by oilseeds and pulses. Sugarcane continues to expand.
Cropping (or land-use) intensity	Change in net sown area coupled to population growth.	Change in net sown area coupled to population growth.	Change in net sown area coupled to population growth.	Change in net sown area coupled to population growth.	Change in net sown area coupled to population growth.	Rapid expansion to maximum cropping intensity in irrigated areas.
Water management						
Cropping (or land-use) intensity	Change in net sown area coupled to population growth.	Change in net sown area coupled to population growth.	Change in net sown area coupled to population growth.	Change in net sown area coupled to population growth.	Change in net sown area coupled to population growth.	Rapid expansion to maximum cropping intensity in irrigated areas.
Irrigated share	All expansion of net sown area to rainfed production.	Expansion of net sown area to both irrigated and rainfed production.	All expansion of net sown area to rainfed production.	All expansion of net sown area to rainfed production.	Expansion of net sown area to both irrigated and rainfed production.	All expansion of net sown area to irrigated production.
Water management	Groundwater use is allowed without limits.	Groundwater use is allowed without limits.	Groundwater use is allowed, overextraction is not.	Groundwater use is allowed without limits.	Groundwater use is allowed without limits.	Groundwater use is allowed without limits.
Crop management						
Production intensity	Emphasis on sustainable resource use instead of economic gains reduces yield gap closure to 0.45% per year.	Continuation of present rate of agricultural input-driven yield gap closure of 0.55% per year.	Strong limitations on further intensification to save aquatic ecosystems, with further yield gap closure driven only by sustainable technological advancements at 0.30% per year.	Some limitations on present day intensification practices are imposed to reduce water quality impact, with yield gap closure reducing to 0.45% per year.	Some limitations on inputs are compensated for by technological advancements, resulting in yield gap closure remaining stable at 0.55% per year.	Unrestrained use of agricultural inputs, disregarding environmental impacts, increases yield gap closure to 0.70% per year.

2015). To optimally use the available land for food production, expansion of net sown area is primarily focused on irrigated areas. Lastly, production intensification is increased compared to the present in the SSP3 scenario and remains stable in the SSP1 scenario.

4.2.3. Quantifying and spatializing land-use projections

Next, we operationalized the agricultural land-use component of our six agricultural development strategies by creating land-use change projections that are a spatially-explicit representation of the proposed changes in the narratives. To do so, we used an approach that is similar to that of Wijngaard et al. (2018) and Smolenaars et al. (2022), in which projected growth rates for each crop group are applied at annual timesteps to the spatially explicit MIRCA-2000 dataset of historical cropping intensity for 2005 (Portmann et al., 2010). An exact overview of the steps can be found in Appendix C.

We applied this procedure for each of the six strategies and for both cropping seasons (Rabi and Kharif). Over 96% of the Indus basin agricultural output, and the entirety of the contiguous Indus Basin Irrigation System, are located on the Indus plains. Significant changes to the Indus basin agricultural system in our assessment were therefore assumed to only occur in the lower Indus basin (see Figure 4.1A). We accordingly only developed spatial land-use change projections for the Pakistani and Indian share of the Indus basin. For the upper Indus basin, the situation as provided by Smolenaars et al. (2022) was maintained. Our approach provided a set of six transient and spatial (5 arcmins) land-use change projections at seasonal timesteps for the lower Indus basin over the period 1950-2080 (see Figure 4.2).

4.2.4. Modelling framework & protocol

To spatially determine the effect of agricultural system changes on future water and food security, we used a fully distributed modelling framework consisting of a one-way coupling between the *Spatial Processes in Hydrology* (SPHY) model (Lutz et al., 2014) and the *Lund-Potsdam-Jena managed Land* (LPJmL) model (Bondeau et al., 2007). The SPHY-LPJmL model coupling has been developed specifically to simulate the interaction between climate change, hydrology and food production in the river basins of High Mountain Asia. It has likewise been applied in multiple integrated studies of the water-food systems of South Asia (Biemans et al., 2019b; Smolenaars et al., 2022; Wijngaard et al., 2018) that include the Indus basin. An elaborate description of the model coupling, calibration and validation can be found in Biemans et al. (2019b). The modelling framework in this study consisted of two parts:

- For the mountainous, and glacier-dominated upper Indus, we used existing projections by the SPHY cryosphere-hydrology model. This model simulates run-off in mountainous areas at 5km resolution and daily timesteps (Lutz et al., 2014). We used SPHY discharge projections for the upper Indus over the period 1980-2080 (Wijngaard et al., 2017) that were generated with the same climate-forcing data as used in this study (Lutz, ter Maat, et al., 2016). We used both naturalized discharge and discharge that was corrected for present and future water usage in the upper Indus basin (Smolenaars et al., 2022).
- The SPHY discharge at the outlets of upper Indus tributaries was used as daily inflow in the LPJmL model, which we applied for the irrigation-dominated lower Indus basin. LPJmL is a crop hydrology model that dynamically simulates the interactions between agricultural practices and hydrology at 5 arcmin resolution and at daily timesteps (Bondeau et al., 2007). The version of LPJmL that we used is specific to South Asia, and allows for the simulation of double cropping, reservoir operation and irrigation networks (Biemans et al., 2016). We recalibrated the crop yields of LPJmL at sub-national level for the 2003-2008

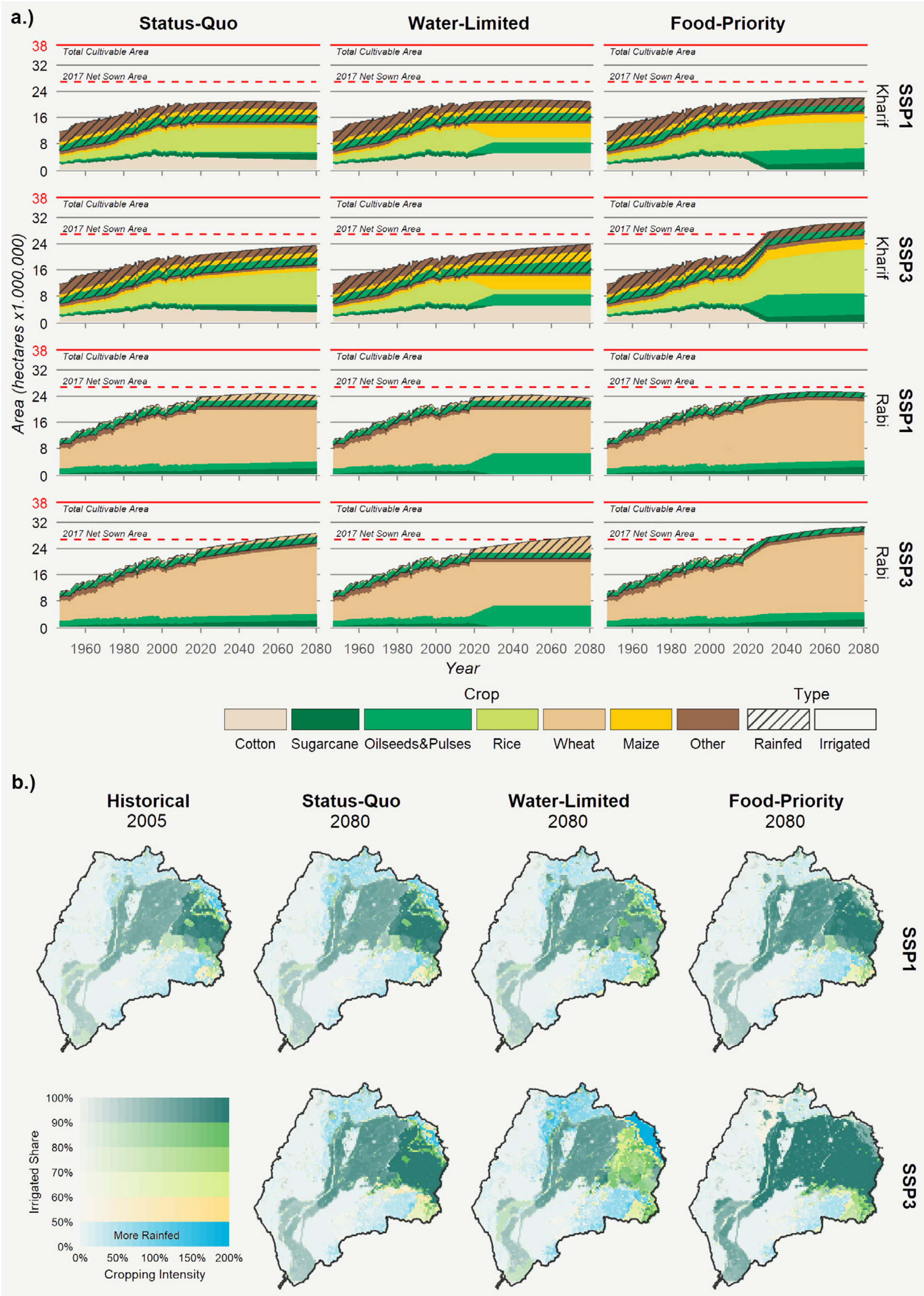


Figure 4.2: Total net sown area per crop type group in the Indus basin, for each strategy, scenario and cropping season (a.), and spatial cropping intensity and irrigation intensity (.b). Note that areas marked in blue in this map are predominantly rainfed.

Table 4.2: average crop production per capita (kg/cap/year of net crop production) and % change (between brackets) compared to the 2000-2020 baseline for the entire Indus basin. Future values account for changes in land-use and crop mix (as per the agricultural development strategies) and in climate.

SSP	Period	Strategy	Crop							
			Wheat	Rice	Maize	Cotton	Sugar-cane	Oilseeds & Pulses	Other	Total (kcal. /cap/year)
SSP1	1980-2000		192 (-10%)	82 (-16%)	25 (13%)	9 (3%)	288 (-1%)	20 (6%)	116 (80%)	3328 (-1%)
	2000-2020		213 (0%)	98 (0%)	22 (0%)	9 (0%)	292 (0%)	19 (0%)	64 (0%)	3359 (0%)
	2030-2050	Status-Quo	216 (1%)	78 (-20%)	22 (-2%)	11 (15%)	395 (35%)	19 (1%)	71 (10%)	3404 (1%)
		Water-Limited	133 (-38%)	13 (-87%)	47 (110%)	13 (48%)	13 (-96%)	41 (118%)	49 (-23%)	2372 (29%)
		Food-Priority	205 (-4%)	84 (-14%)	17 (-23%)	9 (1%)	344 (18%)	37 (96%)	64 (0%)	4009 (19%)
	2060-2080	Status-Quo	225 (6%)	76 (-22%)	21 (-5%)	12 (31%)	527 (80%)	22 (14%)	85 (33%)	3747 (12%)
		Water-Limited	138 (-35%)	13 (-87%)	46 (106%)	17 (89%)	15 (-95%)	46 (146%)	57 (-10%)	2543 (-24%)
		Food-Priority	262 (23%)	86 (-12%)	27 (21%)	0 (-100%)	638 (118%)	41 (118%)	106 (65%)	4529 (35%)
SSP3	2030-2050	Status-Quo	205 (-4%)	84 (-14%)	17 (-23%)	9 (1%)	344 (18%)	17 (-10%)	64 (0%)	3125 (-7%)
		Water-Limited	152 (-29%)	14 (-86%)	47 (110%)	13 (47%)	11 (-96%)	51 (168%)	58 (-10%)	2578 (-23%)
		Food-Priority	235 (10%)	110 (12%)	29 (28%)	0 (-100%)	410 (40%)	47 (151%)	80 (24%)	4063 (21%)
	2060-2080	Status-Quo	171 (-19%)	66 (-33%)	13 (-41%)	11 (17%)	327 (12%)	14 (-24%)	57 (-11%)	2732 (-19%)
		Water-Limited	126 (-41%)	10 (-90%)	35 (55%)	17 (89%)	11 (-96%)	42 (124%)	51 (-21%)	2179 (-35%)
		Food-Priority	195 (-8%)	89 (-9%)	18 (-18%)	0 (-100%)	389 (33%)	37 (95%)	69 (8%)	3490 (4%)

period and compared this to historical production statistics from 1980 to 2015, showing a good agreement (see Appendix Figure C7). The dynamic input data for our LPJmL runs consisted of the SPHY inflow, the agricultural system strategies developed in this study, and downscaled climate forcing data for eight GCMs, including CO2 concentrations(Lutz, ter Maat, et al., 2016). In addition, we accounted for the effect of changing water use of the domestic and industrial sectors due to socio-economic development. Spatial projections for these sectors, which are consistent with the scenarios used in this study, were obtained from Smolenaars et al. (2021) and Smolenaars et al. (2022) on the basis of the regression models by Bijl et al. (2016).

We applied the SPHY-LPJmL modelling framework for each of the agricultural system strategies, and for the two SSP-RCP scenarios with four RCMs per scenario. In these runs, we accounted for climate change, the change in water use by the domestic and industrial sectors, and access to groundwater. To decouple the effect of agricultural system changes from other drivers, we moreover did model runs in which we systematically omitted other drivers. First, we made runs in which we assumed no future agricultural system changes to occur, meaning land-use was kept in 2015 conditions, but climate change and changes in the water-use of the domestic and industrial sectors do occur. Similarly, we made model runs in which we separately omitted the effect of climate change, the change in water use by other sectors, and the unrestricted access to groundwater. Lastly, for each of these model setups, we also did runs with crop yields set at reference, potential or baseline conditions, to simulate the effect of annual yield gap closure. In this manner, we made a total of 154 transient model runs over the period 1950-2080. The simulations provided us with data at high spatiotemporal detail for discharge, water demand, groundwater use and crop yield under each of the strategies for agricultural system change.

4.2.5. Post-processing & indicators

In order to understand how agricultural system changes and other drivers affect water and food security we assessed model outputs using several indicators. For *food security* the following indicators were applied:

- Foremost, we assessed the degree to which food production can meet food demand, using the *caloric self-sufficiency ratio*. We used the FAO dietary energy supply target of 3000 kcal per capita per day(Hubert et al., 2010). This target maintains space for food waste and production losses before reaching the consumer and has been applied in similar modelling studies of future food security (Gerten et al., 2011; Liu et al., 2016).
- To assess the stability of food availability in the Indus basin, we quantified the *impact of climatic variability on food production*. We did this by quantifying, for each grid cell, the variance in net food production per timestep for each strategy between the four climate models (i.e. the variance being only due to climatic variability with all other factors being equal). Next, we determined the influence of this grid-cell variance on the total food production of the basin at the same timestep. We normalized this variance impact value between all scenarios and agricultural development strategies to allow intercomparison between strategies. This indicator demonstrates the climate robustness of each agricultural development strategy under climate change and highlights the areas within the basin that have the largest potential impact on basin level food security in the event of a climate shock.

Similarly, for *water security* we used the following indicators:

- We used the *water withdrawal to availability ratio* (Vörösmarty et al., 2000) at the sub-basin level to determine the effect of the agricultural system changes on water stress. Sub-basins in the irrigated plains of the lower Indus plains were determined at the irrigation-system level, as this is where water allocation decisions are made. For the upper Indus basin, the sub-basins defined in Smolenaars et al. (2022) and Wijngaard et al. (2017) were used. The higher the withdrawal to availability ratio, the more likely severe competition is to occur between different water use sectors, and therefore also with the environment. Likewise, this ratio is affected by more than just agricultural system change. In our simulations, changing water use in other sectors (through its effect on withdrawals) and climate change (through its effect on availability and through the effect of CO2 fertilization on crop water requirements) also affect the ratio. This indicator therefore allowed us to also distill the influence of these other drivers on water stress.
- Moreover, in the Indus basin groundwater is a dependable source of water that provides a buffer for the variable availability of surface water between years and seasons (Laghari et al., 2012). To determine to what extent the Indus water system is able to structurally supply sufficient surface water resources to meet societal needs, and thus suffers from water stress, we assessed the relative importance of groundwater as a water source. *Groundwater dependency* was operationalized by determining the total withdrawal of groundwater and the relative share of groundwater to total water extractions for irrigation.
- An overdependence on groundwater may similarly threaten its sustainability on the long term as a buffer in times of drought (Basharat et al., 2015). We assessed the status of groundwater sustainability at the grid cell level by estimating *groundwater depletion* as applied by Biemans et al. (2019b). Groundwater depletion is estimated as the mean annual difference between groundwater recharge and extraction over multi-decadal periods.
- To assess the effect of agricultural system changes on the environment, we determined the status of *environmental flows* in the Indus river. We used the *Variable Monthly Flow* (VMF) method by Pastor et al. (2019). This approach defines that a minimum of 30% (wet season) and 60% (dry season) of mean natural monthly discharge must be maintained in a river to sustain its environmental qualities. In our study, minimum monthly flow thresholds were determined for the lower Indus using LPJmL, with naturalized vegetation and reference climate for the period 1990-2010. We defined the wet season as May to October and the dry season as November to April (Laghari et al., 2012).

4.3. Results

4.3.1. Impact on food security

Our simulations demonstrate that future food production per capita differs strongly between the agricultural development strategies. However, differences are even greater between the SSP-RCP forcing scenarios. Foremost, Figure 4.3A illustrates that without any agricultural system changes, per capita production in the basin quickly deteriorates. Population growth increases the food demand, while climate change slowly decreases its supply. This ensures that after 2030, the current food production system will structurally not produce enough food to sustain all inhabitants of the basin. Consequently, most regions of the basin will not remain food self-sufficient, except the presently food-exporting Eastern Indus Plains located in India (Figure 4.3B).

Figure 4.3A also illustrates that under the *Water Limited* strategy, the basin cannot be self-sufficient in terms of food production either, regardless of the trajectory of population change. In SSP1, the over-extraction of groundwater is no longer available as a readily available

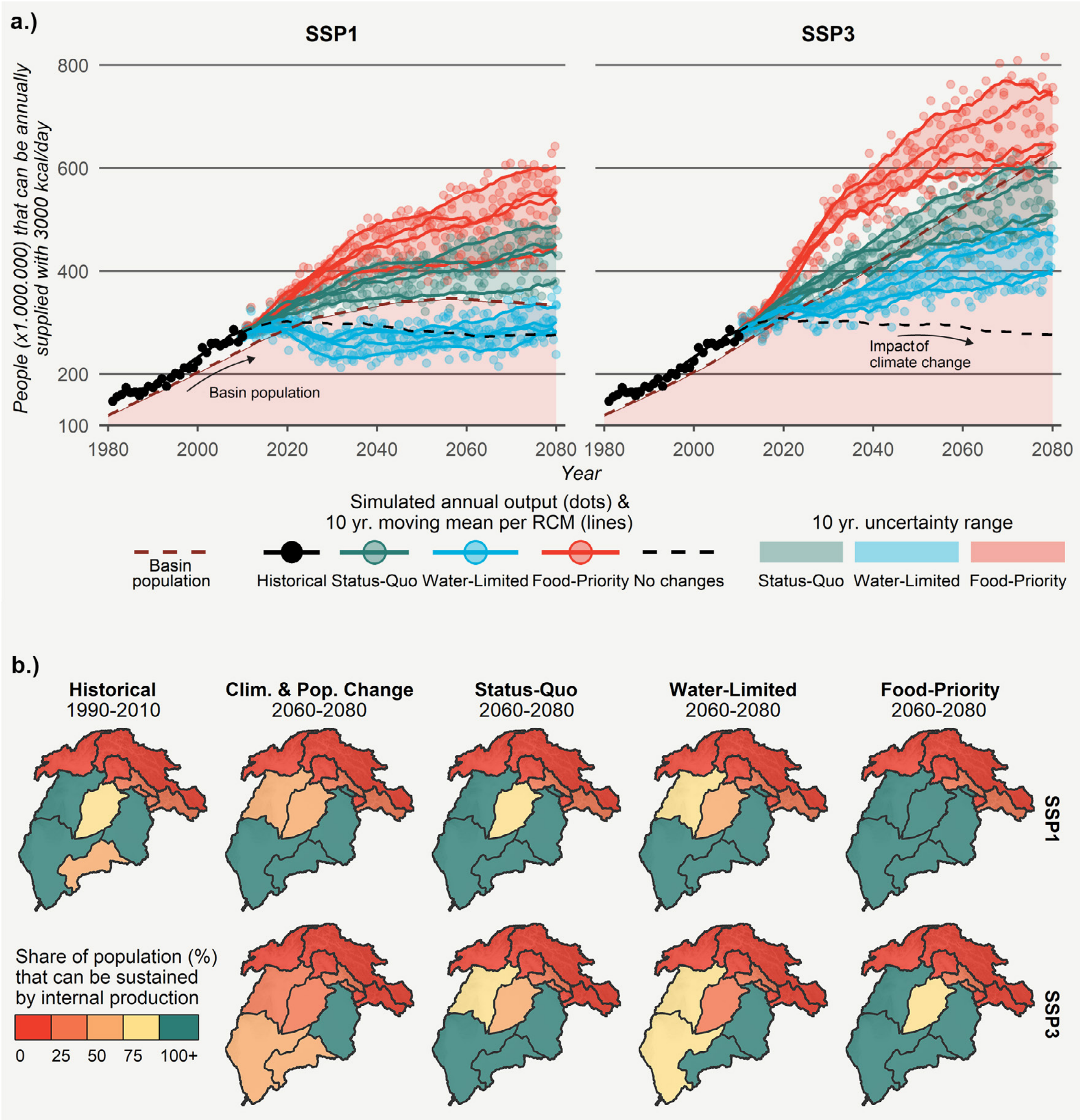


Figure 4.3: Simulated availability of food, in relation to the demand for food, at the basin level (a.), with dots representing the amount of people that can be supplied with sufficient food in a strategy per individually simulated year, and lines the 10 year moving mean of these years per Regional Climate Model (RCM). The maps (b.) show the degree of food self-sufficiency at sub-basin level.

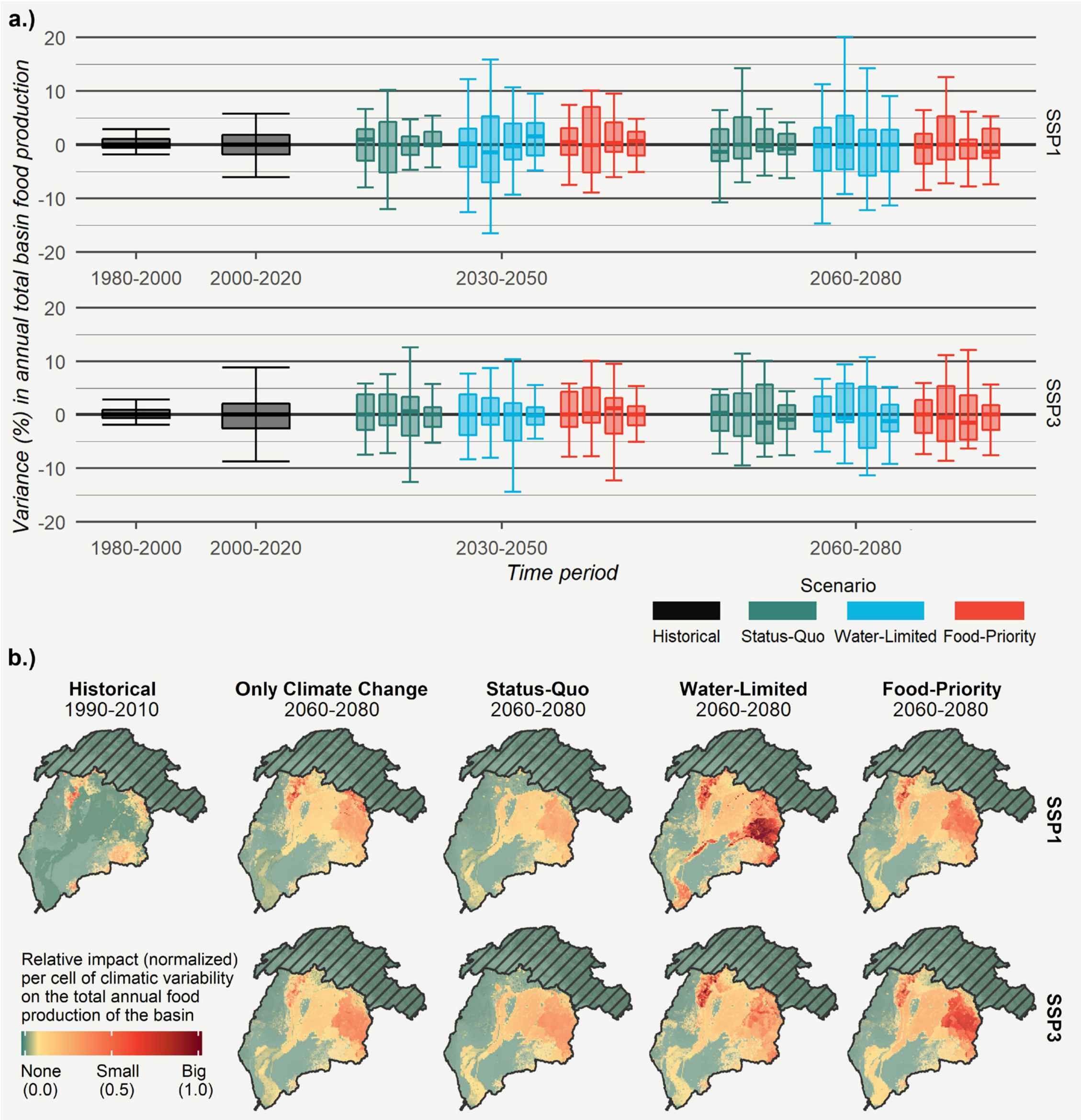


Figure 4.4: Impact of climate variability for different agricultural development strategies on total food production (a.) and hotspots for climate impact (b.). Note that for the upper Indus basin, no simulated data was available due to the geographical scope of the LPJmL model covering only the lower Indus basin.

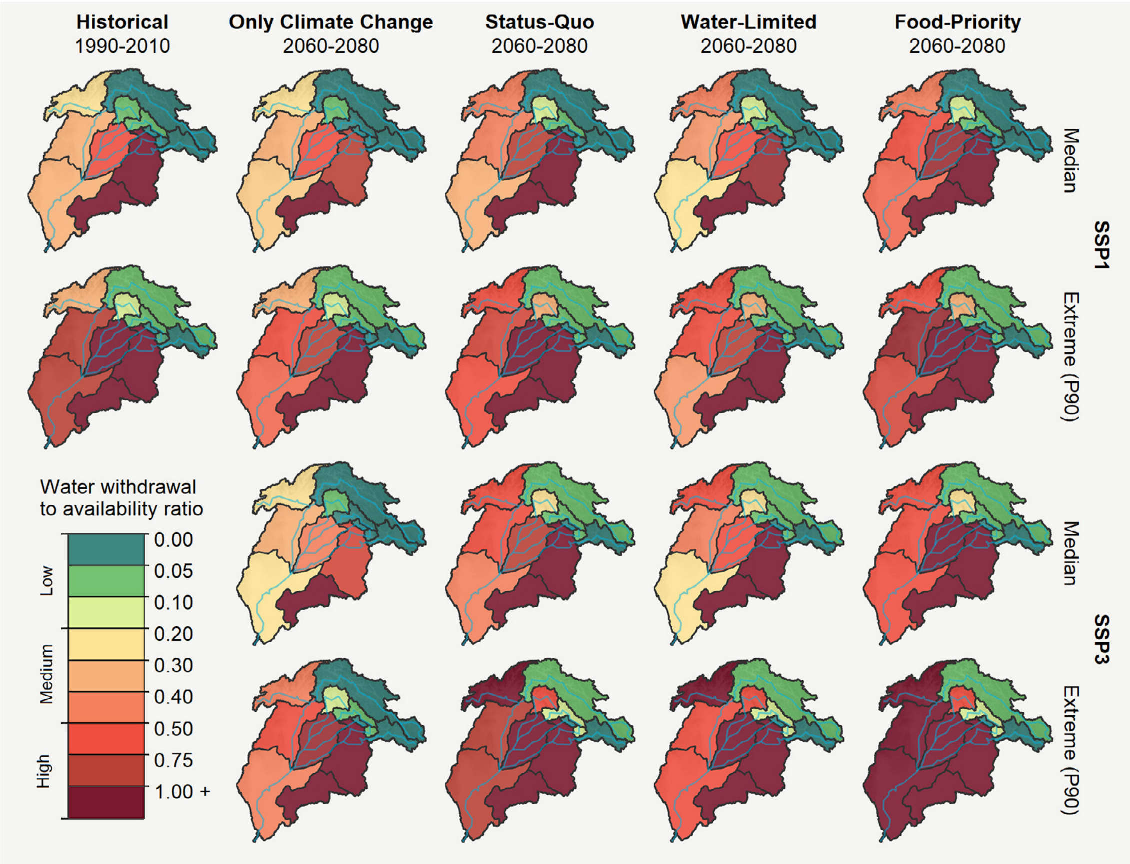


Figure 4.5: Median and extreme (10 year) water stress (per the withdrawal to availability ratio) for historical situation (1st column), under only climate change (2nd column) and for all drivers including agricultural development strategies (3th 4th and 5th column).

supplement to surface water. This causes an initial drop in food production, which is only slowly restored over the course of the century by increasing production efficiency due to technological advancements that are assumed to occur under this strategy. Spatially, the impact on food production is largest in the most agriculturally productive regions of the Indus basin (see Figure 4.2B and Appendix Figure C8). Similarly, Figure 4.4A shows that across all scenario-strategy combinations, the SSP1 *Water Limited* strategy is most sensitive to climatic variability. The omission of groundwater as an unrestricted source of water greatly affects the climate robustness of food production in this strategy (Figure 4.4B). In contrast, the SSP3 *Water Limited* strategy allows present groundwater practices to persist, but not escalate further. Production intensification allows food production to increase on a similar water budget in this strategy. This growth does lag behind its historical pace however, and is therefore not enough to keep up with projected population growth in this scenario. A switch in crop mix moreover causes the per capita availability of staple wheat and rice crops to drop sharply (Table 4.2).

On the other hand, in the SSP1 *Status Quo* strategy, production intensification and limited expansion of rainfed agriculture are sufficient to maintain the present rate of self-sufficiency in the basin. This even occurs under the most unfavorable of four climatic projections for the RCP4.5 scenario (see Figure 4.3A). The *Status Quo* strategy in the SSP3 scenario similarly sees total food production show sufficient growth to keep up with population growth. However, towards the second half of the century, the impact of the more extreme RCP8.5 climate (Figure 4.4B) gradually overtakes the positive impact of yield gap closure. In the SSP3-RCP8.5 scenario only the *Food Priority* strategy manages to secure food self-sufficiency at the basin level by the end of the projected period. Figure 4.2B shows that this strategy moreover improves the food self-sufficiency ratio across several of the basin's sub-regions. The per capita availability of staple rice and wheat remains at current levels (Table 4.2), while the production of oilseeds, pulses and sugarcane strongly increases. This may reduce the need to import these crops. In the SSP1 scenario, *Food Priority* would see the Indus basin, especially the Indian and Pakistani Punjab, produce more than what is locally required. This suggests the region can maintain its role as a bread basket for the wider region (Bishwajit et al., 2013).

4.3.2. Impact on water security

The water withdrawal to availability ratio in the Indus basin is already high in the reference period. This indicates significant water stress (Figure 4.5). Especially the intensively cultivated eastern half of the lower Indus basin faces a median withdrawal-to-availability ratio close to, or above, 1.0. This means that surface water supplies are structurally unable to meet demands. This similarly translates in considerable over-extraction of groundwater in these subbasins (Figure 4.7B). Figure 4.5 demonstrates that the future of water stress and groundwater use here differs strongly between agricultural development strategies. However, Figure 4.6 demonstrates that other drivers (i.e. climate change and changes in the water use for sectors other than agriculture) affect water stress by a similar magnitude. In particular, the positive relation between climate change and surface water availability (Lutz et al., 2019) and the effect of CO2 fertilization on crop water use (Jägermeyr et al., 2016), reduce water stress by up to 50% in some areas of the basin. Increasing water demands for non-agricultural purposes (i.e. domestic and industrial sector) on the other hand strongly increase the ratio of water withdrawal to availability. This effect is strongest in several upper Indus subbasins (see Figure 4.6) where the domestic and industrial sectors account for a larger relative share of total water use due to the limited role of irrigated agriculture (Smolenaars et al., 2022). The central Indus

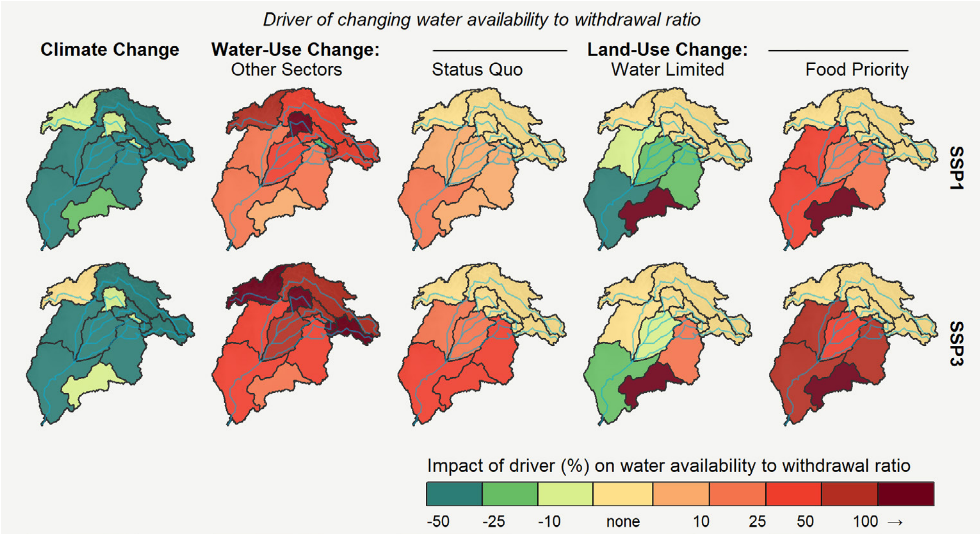


Figure 4.6: Average isolated effect of climate change, changing domestic & industrial use and agricultural system change on future water stress (i.e. ratio water withdrawal-availability).

plains, which contains several fast growing cities, also sees severe influence from this driver in the SSP3 scenario.

Figure 4.6 subsequently illustrates that the *Water Limited* strategy largely reduces agricultural water demand. This subsequently reduces the withdrawal to availability ratio in the lower Indus basin. The future water stress experienced in most subbasins therefore decreases both in median and extreme dry years despite the increase in non-agricultural water withdrawals (Figure 4.5). Only several subbasins in the upper Indus demonstrate an increase in water stress due to the aforementioned expansion in non-agricultural water use. The *Water Limited* agricultural system changes correspondingly reduce the demand for groundwater resources (Figure 4.7A). In the SSP1 scenario groundwater use drops considerably compared to present levels, and over-extraction remains limited to several fast-growing cities that depend on groundwater resources to meet domestic and industrial water demands. The dependency on groundwater similarly drops in favor of surface water, especially in the heavily irrigated eastern Indus plains (Appendix Figure C9). In SSP3, pressure from strong population growth requires groundwater use to increase slightly towards the middle of the century (2030-2050) and then reduce again. Over-extraction therefore remains similar to present levels, but becomes less concentrated in the eastern Indus plains, shifting towards the rapidly urbanizing central Indus plains instead (Figure 4.7B).

In contrast, the *Status Quo* and *Food Priority* scenarios see an increase in both agricultural and non-agricultural water demand in the lower Indus and hence an increase in future water stress (Figure 4.6). The intensification towards full double cropping in the *Food Priority* strategy results in a steep rise in water stress. Figure 4.7A moreover demonstrates that groundwater extractions must double to support such agricultural expansion. The central Indus plains,

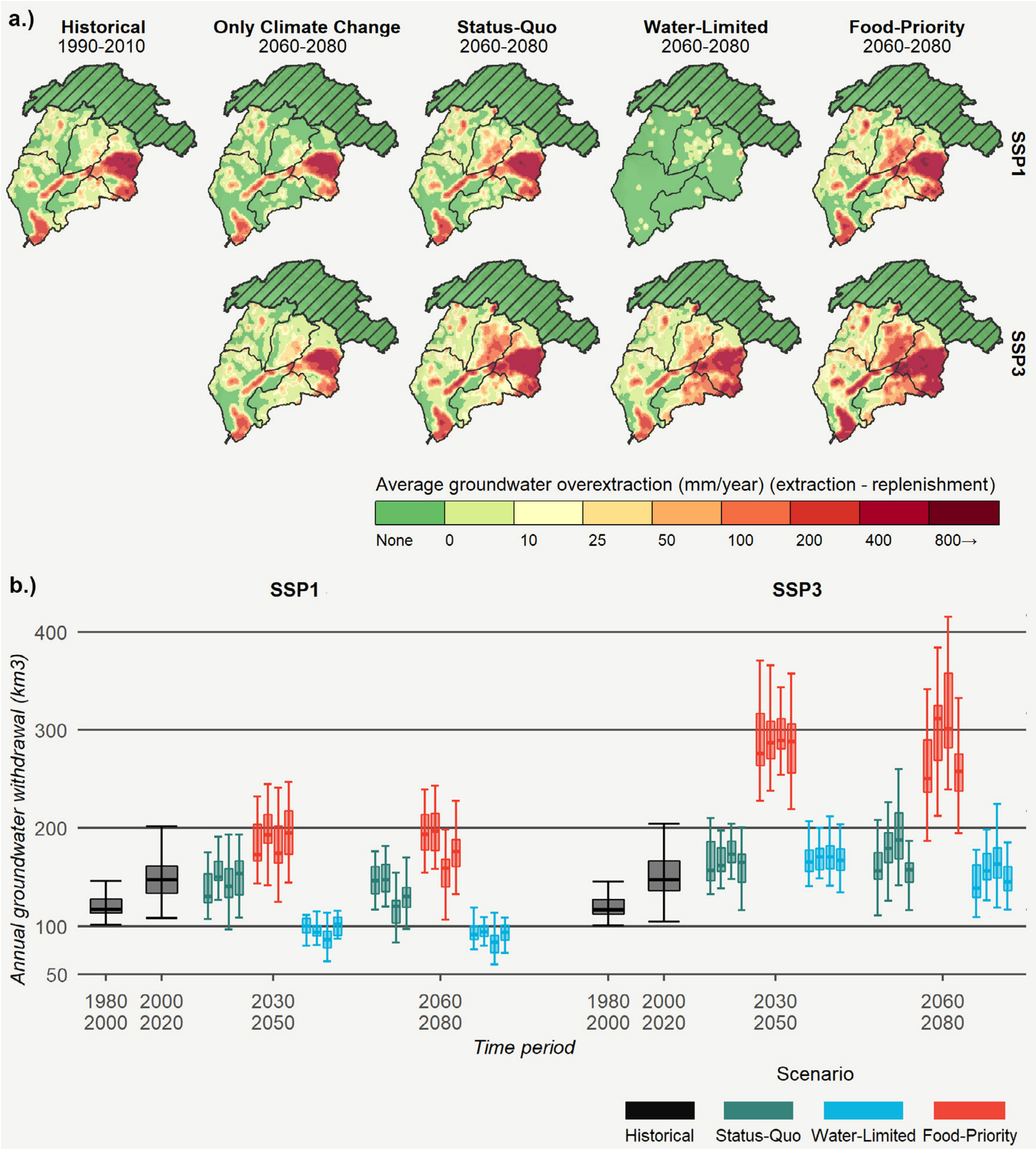


Figure 4.7: Impact of agricultural system changes on total groundwater withdrawals in the basin (a.) and spatial patterns of groundwater overextraction (b.).

located largely in the Pakistani Punjab, demonstrate a similar pattern of groundwater over-extraction as is currently present in the intensively cultivated Indian provinces of Punjab and Haryana. The dependency on groundwater throughout the basin similarly increases strongly (see Appendix Figure C9). The eastern Indus plains are already near full double cropping intensity and likewise face strong over extractions and groundwater dependency in the present. These areas therefore see few changes under these strategies. The *Status Quo* strategy sees groundwater use stay stable in the SSP1 scenario and groundwater over extractions increase slightly around the major cities of the Pakistani Punjab.

4.3.3. Environmental impact

The positive influence of climate change on meltwater availability also translates to environmental flows being met, on average, for a larger period of the year (Figure 4.8). However, increased water consumption for domestic and industrial purposes largely negates these benefits, especially in the western tributaries of the Indus river. Changes in agricultural water demand brought on by the agricultural development strategies have similar impacts on environmental flows as they do on water stress. Under the *Water Limited* strategy, environmental flows considerably improve compared to the reference period (2000-2020) and to the situation without agricultural system changes. Especially in the ecologically important Indus delta (Laghari et al., 2012) minimum flow requirements are met more often in the SSP1 scenario. However, under the *Status Quo* and *Food Priority* strategies, the situation in the western tributaries worsens in comparison to the situation without agricultural system changes. This is especially the case downstream of the Jhelum river. In Figure 4.6 the two easternmost tributaries demonstrate large increases in future discharge under climate change and subsequently see the status of environmental flows largely improve under all strategies and scenarios.

4.4. Discussion

4.4.1. Limitations and opportunities

In this study we investigated the influence of three alternative agricultural development strategies on future water and food security in the Indus basin under two contrasting scenarios of integrated climatic and socioeconomic change. The *Water Limited* and *Food Priority* strategies were developed from the perspective of adaptation policymaking. By design, these strategies represent relatively extreme and hypothetical positions, embodying strongly divergent perspectives in the water-food debate. We assume for these strategies that rapid and structural changes based on top-down directives are implemented universally throughout the Indus basin by 2030. This requires strong institutional capacity, and the financial tools to effectively influence farm-level choices (Clapp, 2017). Such governance may be feasible in the optimistic SSP1-RCP4.5 scenario, but will be more challenging in the disrupted future of SSP3-RCP8.5 (Smolenaars et al., 2021). Our scenario analysis hence demonstrates the bandwidth of influence that agricultural system changes can have on water and food security and thus its potential in support of achieving SDG2 and SDG6. However, future studies could consider an incremental approach to agricultural system change, exploring individual measures and moderate sets of changes, as this may help identify more feasible initial policy priorities in the basin.

On the other hand, several autonomous farm-level changes are not accounted for in our policy-oriented strategies. For example, although we considered yield gap closure through increased nutrient use and crop management, other adaptations to farming systems such as different

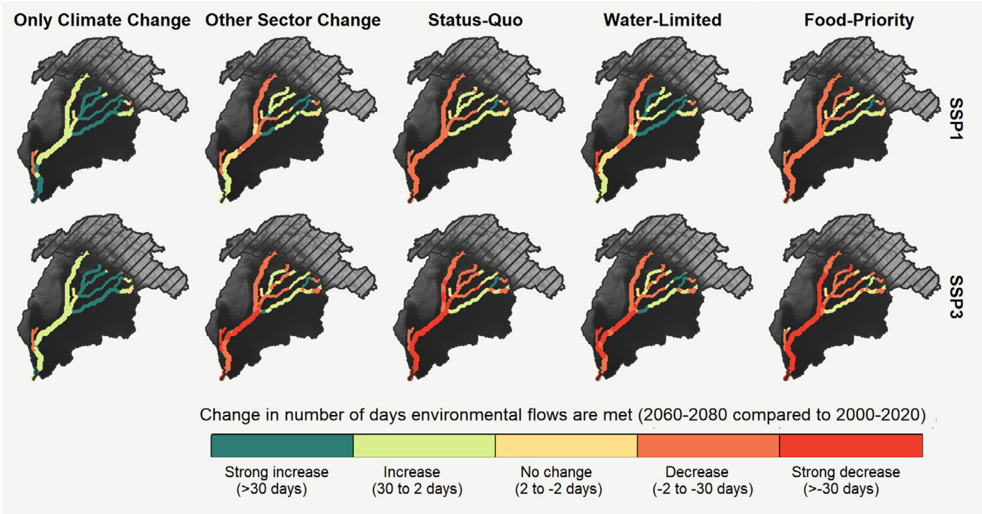


Figure 4.8: Average future impact on environmental flows for the Indus river and main tributaries (average annual flow > 10km3) per strategy, on top of relief base map.

farm-level irrigation and water management techniques (Ostad-Ali-Askari, 2022), new crop varieties and changes in sowing and harvesting dates(Kirby et al., 2017) were not part of our assessment. Our results indicate that after 2050, climate change considerably decreases potential yields of several staple crops, especially due to higher temperatures. Farm-level adaptation and innovation could potentially moderate some of these impacts (Shahbaz & Boz, 2022; Tariq et al., 2014). However the options to adapt to the projected severe heat stress in the Indus Basin are still relatively limited (Droppers et al., 2022). Further scenario-based modelling assessments focused on farm-level changes are required to understand the effect of such bottom-up changes, in addition to the top-down strategies considered here. For example, research by Jamil et al. (2023) has shown that laser-land-leveling may be a promising technical intervention to simultaneously reduce irrigation water demands and boost yields. A thorough upscaling assessment must be conducted to explore if such measures are indeed as beneficial at the basin scale as they are at the field level.

Our assessment also did not consider the effect of agricultural system changes on water quality, and the effects of changing water quality on food and water security. Currently, pollution in the Indus river and its tributaries is rampant and has a considerable effect on human and ecosystem health (Rasul, 2016). A major source of water pollution is the improper use of agricultural inputs (Shahbaz & Boz, 2022). Similarly, extensive pumping of brackish groundwater to sustain irrigation systems in the lower Indus is driving soil salinization and reducing water quality (Salam et al., 2020). Both factors are likely to increase under agricultural system intensification, especially in the *Food Priority* strategy which relies heavily on additional nutrient use and groundwater irrigation. An increase in grey water footprint may decrease the surface water that is of suitable quality to be used in agriculture and subsequently negatively affect food production (Shahbaz & Boz, 2022). Similarly, it may drive additional groundwater over-extraction. This feedback loop will be of critical importance for the water stress experienced in the basin, especially in regions downstream(Yoon et al., 2015). Future studies should therefore look to integrate water quality and water quantity metrics in their assessment of water stress and water-food interactions in the Indus basin.

4.4.2. Implications and recommendations

The results of this study demonstrate clearly that the direction in which the Indus agricultural system develops will strongly affect the potential achievement of SDGs for food, water and aquatic ecosystems (SDG 2, 6 & 15). The degree and type of impact is however determined largely by other regional drivers. In particular, increasing water and food demands due to population growth were found to greatly increase pressure on indicators for the beforementioned SDGs. The *Water Limited* and *Food Priority a*gricultural development strategies are shown to be able to mitigate this impact for the respective sector they are targeted at, but at the same time compound the pressure on the other SDGs. The *Status Quo* strategy sees indicators for SDGs related to both water and food security deteriorate. No single strategy can ensure improvements for indicators of all SDGs under climate change and socioeconomic development.

Our results specifically show that, to remain food self-sufficient with a growing population, both production and cropping intensifications are needed for the Indus basin. This will require substantial increase in irrigation water use for agricultural purposes. Agricultural water demands must however increasingly compete with rising water demands for domestic and industrial purposes (Laghari et al., 2012). Similar to Kirby et al. (2017) we find that sustaining food production at current per capita levels in the *Food Priority* strategy therefore compounds stress on the Indus water system. Moreover, this also increases the dependence of agriculture on groundwater by over 50%. At present, highly intensive agriculture in the Indian share of the basin already structurally overexploit groundwater resources (Salam et al., 2020). This results in a drop in groundwater tables which may progressively limit its (economic) accessibility to agriculture (Muzammil et al., 2021). Previous studies have therefore deemed these agricultural systems to be untenable in the long-term (MacAllister et al., 2022; Sidhu et al., 2021). The expansion of this agricultural model throughout the basin in the *Food Priority* strategy keeps per capita food production at present-day levels, but also sees similar groundwater issues aggravate in the Pakistani Indus plains. The pursuit of SDG2 through continued agricultural systems intensification thereby not only inflicts severe negative trade-offs on water security for society and the environment, putting SDG6 and SDG15 at risk, but may also accelerate the structural depletion of water availability for food production itself (i.e. water security of food security).

Conversely, we show that improvements to water security and improving environmental flows in the Indus basin are possible with a drastic shift towards sustainable agricultural water management in the *Water Limited* strategy. Total food production still increases, but our assessment demonstrates this to be outpaced by the growth in food demand in both SSP1 and SSP3. Food self-sufficiency can consequently not be achieved in large parts of the basin under this strategy. However, regional self-sufficiency is a critical economic factor in ensuring low-income households have stable access to food (Hubert et al., 2010). Gaps in local availability may be compensated by food imports, but have a destabilizing effect on food prices and therefore food security for the most vulnerable groups (Clapp, 2017). Moreover, the riparian states of the Indus basin currently face severe trade deficits (MoCI, 2021; PBS, 2021). Agricultural products (i.e. basmati rice, cotton) are among the main regional exports and generate the capital required to import other food products, like edible oils. A shift away from export crops and an increased dependence on food imports may thus be economically infeasible. Similarly, the complex hydropolitical relations between riparian states dictate that food self-sufficiency is an important national security objective (Rasul, 2016) as trade disruptions cannot be discounted (Baer-Nawrocka & Sadowski, 2019). Agricultural system changes focussed on achieving SDG6 and SDG15 in the Indus basin may therefore carry strong negative trade-offs for SDG2, especially in a future characterized by high population growth, limited economic development and political isolationism (SSP3).

The complexity of these SDG trade-offs highlights that environmental boundaries likely exist for the capacity of agricultural system changes in the Indus basin to both ensure future food self-sufficiency and improve basin-level water security. This suggests that agricultural development strategies must be supported by Climate-Smart technical innovations that can realize drastic improvements to crop-water productivity (Kirby et al., 2017). However, the trade-offs also demonstrate that a paradigm shift may additionally be needed with regards to the role of the agricultural system in the water-food Nexus of the Indus basin. Foremost, the discussion on basin-level food security must expand beyond rigorously ensuring regional food production (i.e. availability) matches demand. Increased food imports, in particular for non-staple but highly water-consumptive crops like sugarcane, appear important to reconcile sufficient food availability with sustainable water use on the long-term, especially under rapid population growth seen in SSP3. This additionally requires water-food adaptation, and future studies in support of this process, to focus not only on optimizing food production. The inclusion of other socioeconomic factors, such as household food access, economic development (Clapp, 2017) and the stability of inter-basin cooperation (Vinca et al., 2020), can make alternative strategies based on partial food imports more politically feasible and mitigate its disadvantages for food security. Agricultural system changes are therefore an important adaptation mechanism for water and food SDGs, but must be integrated into development pathways that convey a broader view on sustainable adaptation to balance or mitigate trade-offs between sectors.

4.5. Conclusions

This study shows that the direction in which the agricultural system develops will strongly influence the SGDs for water (SDG2 and SDG15) and food (SDG6) security in the Indus basin. Agricultural system changes can provide considerable support to achieve individual SDGs, but are also characterized by strong intersectoral trade-offs between water and food availability on the long-term. No single strategy is able to achieve improvements by 2060-2080 for all indicators at the same time. To maintain the per-capita production of staple crops at sufficient levels under population growth, a considerable increase in water for agriculture is needed. This is shown to strongly increase water stress and groundwater overexploitation throughout the basin, especially in the Pakistani central Indus plains. Agricultural system change focused on sustainable water management on the other hand can achieve a reduction in irrigation water use. This reduces water stress and provides space to growing water demands of sectors other than agriculture, but does have the consequence that food self-sufficiency cannot be achieved in many regions of the basin in the future.

Our study therefore indicates that agricultural system changes are an important adaptation mechanism on the road to a water and food secure Indus basin. However, agricultural development must be incorporated within broader adaptation strategies that can offset its negative trade-offs, particularly when it comes to moderating agricultural water use. Subsequent studies may therefore assess the viability and implications of Climate-Smart innovations that can increase the crop water productivity of the current agricultural system. However, under continued high population growth, biophysical and societal limits on irrigation water availability may make a regionally self-sufficient food system unreconcilable with sustainable water management. Integrated adaptation strategies for water and food security in the Indus basin should therefore not only aim to achieve an increase in regional food production on a smaller water budget through technical interventions, but also emphasize socioeconomic changes that may lessen the drawbacks of potential increases in food imports for household and national food security.

Acknowledgements

Work of all the authors is supported by the SustainIndus project funded by NWO Wotro (Project W 07.30318.002), the Interdisciplinary Research and Education Fund (INREF) of Wageningen University and Research, and Utrecht University. HB would like to acknowledge partial funding from Wageningen University and the Food Security and Valuing Water research program supported by the Dutch Ministry of Agriculture, Nature and Food Security. SD acknowledges partially support by Sustainable Development Investment Portfolio (SDIP), the Department of Foreign Affairs and Trade (DFAT), Government of Australia, the Swiss Agency for Development and Cooperation (SDC) and by core funds from ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland and the United Kingdom. The views and interpretations in this publication are those of the authors, and they are not necessarily attributable to their organizations.

5. Adaptation Pathways

Wheat or Water? Spatial pathways to reconcile water and food security in the Indus basin

Irrigated wheat production is critical for food security in the Indus basin. Changing climatic and socioeconomic conditions are expected to increase wheat demand while reducing irrigation water availability. Adaptation of irrigated wheat production is therefore needed to achieve the interlinked Sustainable Development Goals (SDGs) for water and food security. Here, we present a spatial adaptation pathways tool that integrates water and food objectives under future climate change and population growth. We find that pathways have sufficient adaptive space on the short-term to ensure both wheat production increases and irrigation water savings. However, for high-end future population estimates, pathways must ultimately prioritize either water or food security. Adaptation planning for the SDGs in the basin must therefore anticipate that the current food production system may be untenable. Spatial pathways can incorporate the heterogeneity in local conditions within regional adaptation strategies, which allows for an improved representation of complex adaptation challenges.

Submitted as: Smolenaars, W.J., Sommerauer, W.J., van der Bolt, B., Jamil, M.K., Dhaubanjar, S., Lutz, A.F., Immerzeel, W.W., Ludwig, F., Biemans, H. (2023). "Wheat or Water? Spatial pathways to reconcile water and food security in the Indus basin." Nature Sustainability.

5.1. Main

The Indus plains, shared by India and Pakistan, are one of the most productive agricultural zones in the world. The region is considered the breadbasket of South Asia and produces enough food to sustain over 300 million people. Agriculture on the arid Indus plains depends strongly on irrigation, which has led to the largest contiguous irrigation system in the world (Laghari et al., 2012). During the monsoon season, precipitation and glacial melt in the upper Indus basin provide ample surface water for downstream irrigation through a vast system of tributaries and canals (Smolenaars et al., 2022). However, in the dry rabi season, mountain water availability and precipitation are limited, and irrigation demands are largely met through local groundwater extractions (Biemans et al., 2019b). In the most intensively cultivated areas of the plains, this has caused groundwater tables to drop by several centimeters per year (Sidhu et al., 2021). Overuse of scarcely available surface water during the dry season causes extensive damage to aquatic ecosystems of the Indus river and tributaries (Laghari et al., 2012). The crop responsible for the major part of dry season water demands is winter wheat (Kirby et al., 2017). Wheat is however also a staple crop for regional diets and considered a key pillar of food security. Regional self-sufficiency in terms of wheat production is an important policy objective for the riparian states of the basin and important to support the zero-hunger Sustainable Development Goal (SDG2).

The future outlook for wheat production and the feasibility of maintaining self-sufficiency are uncertain. The Indus basin population has nearly doubled in the last few decades, and a continuation of population growth (UN, 2015b), resulting in increased wheat demand, is expected for the upcoming decades (Smolenaars et al., 2021). Wheat yields are moreover sensible to heat stress, which will increase as climate change impacts progressively become more severe (Droppers et al., 2022). The availability of surface water for irrigation is in addition changing, partly due to a shift in timing with climate change (Wijngaard et al., 2018), but also due to growing water demands from other water-use sectors (Flörke et al., 2018). Research by Lutz et al. (2022) showed that without adaptation, these combined processes will increase groundwater dependence for agriculture in the Indus basin during late monsoon and dry season. This is likely to exacerbate existing trade-offs between wheat production and short-term food security objectives on the one side, and long-term water security objectives on the other. Singh and Park (2018) similarly deemed the current relation between staple crop production and groundwater use in the most intensively managed agricultural systems of the basin as unsustainable. Adjusting wheat production on the Indus plains to rapidly changing circumstances is therefore needed to maintain both sufficient wheat availability towards achieving SDG2 and to support sustainable water management (SDG6).

Previous studies investigated options for integrated water-food adaptation in the Indus basin by analyzing the effect of large sets of adaptation measures (Vinca et al., 2020; Smolenaars et al., 2022). These studies evaluate the full potential of particular adaptation strategies, but do not demonstrate the magnitude, timing and sequencing of actions required to attain explicit societal objectives through time for water and food security. The type and timing of adaptation is however challenging to anticipate for the long-term due to the uncertainty surrounding climatic and socioeconomic changes. Tanaka et al. (2015) instead used an 'adaptation pathways approach' to develop quantitative adaptation steps which incrementally counteract the effect of climate change on global wheat production. The sequential nature of adaptation pathways embraces uncertainty and allows adaptation to develop flexibly alongside the trajectory of

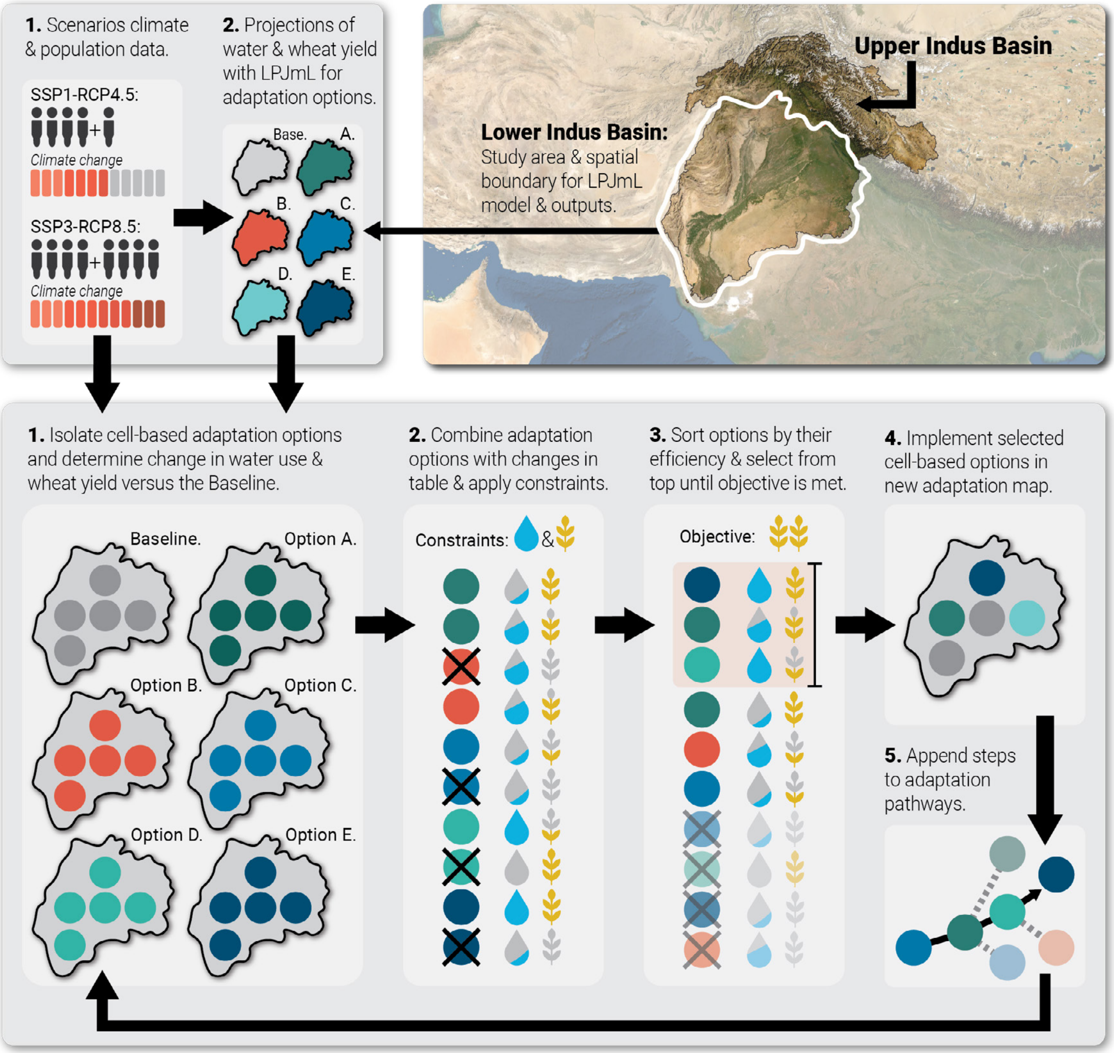


Figure 5.1: Geographical overview of study area (top right), and conceptual representation of the major procedures within the Spatial Pathways Algorithm (bottom) and its input data (top left).

future changes (Kwakkel et al., 2016). Pathways are however a relatively new approach, and quantitative applications have largely focused on climate change adaptation towards clearly-defined sociotechnical objectives, such as flood defenses (Werners et al., 2021). Methods to quantitatively integrate additional societal processes, both as stressor and as source for multiple contesting objectives, remain limited. Additionally, pathways approaches are often applied at regional scale without spatial dimension. Ensuing pathways can subsequently demonstrate the type and timing of adaptation, but not the location. This leaves existing approaches with little capacity to represent the scale-gap between policy objectives at the regional level and the diversity in local conditions in which adaptation towards these objectives must occur (Cradock-Henry & Frame, 2021).

Here, we present a novel adaptation pathways approach that is spatiotemporally explicit and capable of simultaneously pursuing multiple water and food security objectives (see Figure 5.1). This approach is therefore better able to represent the unique adaptation context of irrigated wheat production in the Indus basin. We applied the approach to construct four sets of pathways with different objectives and priorities for future wheat production and irrigation water savings. The pathways address climatic and population changes for the optimistic RCP4.5-SSP1 (moderate climate change, population stabilization) and pessimistic RCP8.5-SSP3 (extreme climate change, continued population growth) scenarios (Riahi et al., 2017). Pathway construction considered three adaptation measures: production intensification (BSPR), laser-land levelling (LLLV), and the expansion of irrigated area through the partial (EXPD) or full (HIST) reappropriation of irrigation water savings. Combinations between these measures provide five distinct adaptation options. We obtained spatial data on the effects of adaptation options and climate change on wheat yields and irrigation water demands with the fully distributed LPJmL crop-hydrology model (Biemans et al., 2019b). We additionally determined how climatic and population changes affect future wheat availability and irrigation water demands in the absence of adaptation (i.e. Reference pathways). The pathways allow insight, through space and time, into the long-term feasibility and trade-offs for integrated adaptation towards SDG2 and SDG6 in the Indus basin. This method advances the potential of threshold-oriented approaches (Werners et al., 2021) by demonstrating how multiple sociopolitical interests can be integrated and expressed spatially.

5.2. Results

5.2.1. Impact of climate change and population growth

The Reference pathways demonstrate in Figure 5.2 that climate change will reduce wheat production by 14% in 2080 compared to 2015 in the SSP1-RCP4.5 scenario and almost 20% in the SSP3-RCP8.5 scenario. In combination with population growth, this causes annual wheat production per-capita to reduce from 200kg currently to approximately 145kg in SSP1-RCP4.5, and only 60kg SSP3-RCP8.5 (see Figure 5.2B). In Pakistan, meeting per-capita wheat consumption, estimated at 150kg per annum, is an important production threshold for national policy (Zulfiqar & Hussain, 2014). Even with minimal population growth and moderate climate change, wheat production will thus not be adequate to ensure food security by 2040 if no adaptive actions is taken. Figure 5.3 shows that climate change, through the combined effects of precipitation change, CO2 fertilization and shortening growing season due to higher temperatures (Wijngaard et al., 2018), will decrease irrigation water demands. In the SSP1-RCP4.5 scenario, water demands considerably reduce in the first part of the century and stabilise after 2050. The SSP3-RCP8.5 sees this downward trend continue over the entire projected period as climate change remains unmitigated. The reduction in irrigation

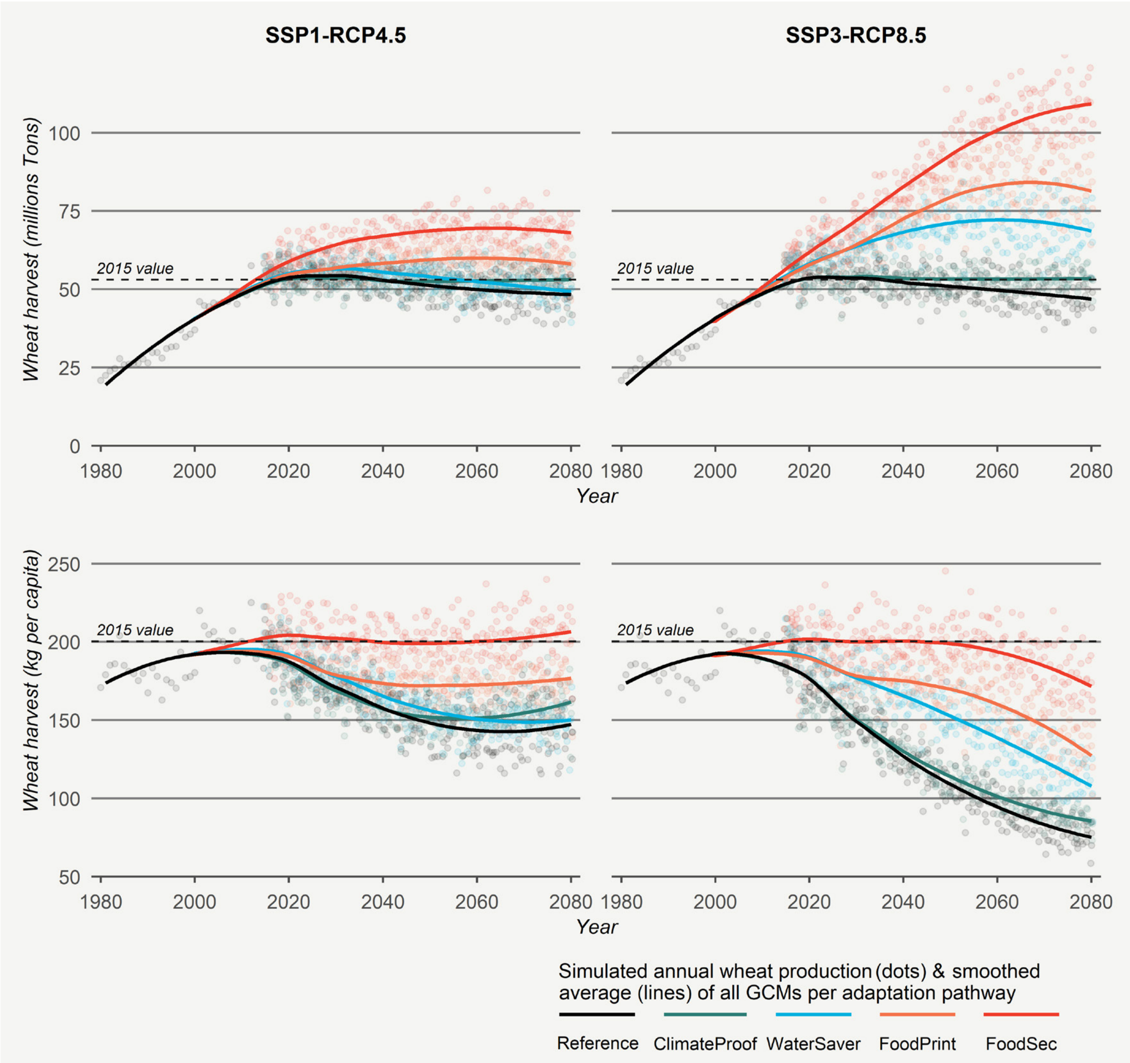


Figure 5.2: Historical wheat production (in total, top, and per capita, bottom) and projected production for the adaptation pathways. The dots represents the individual simulated production per year for each of the GCMs (i.e. four dots per pathway per year). The lines represents the smoothed average of all GCMs.

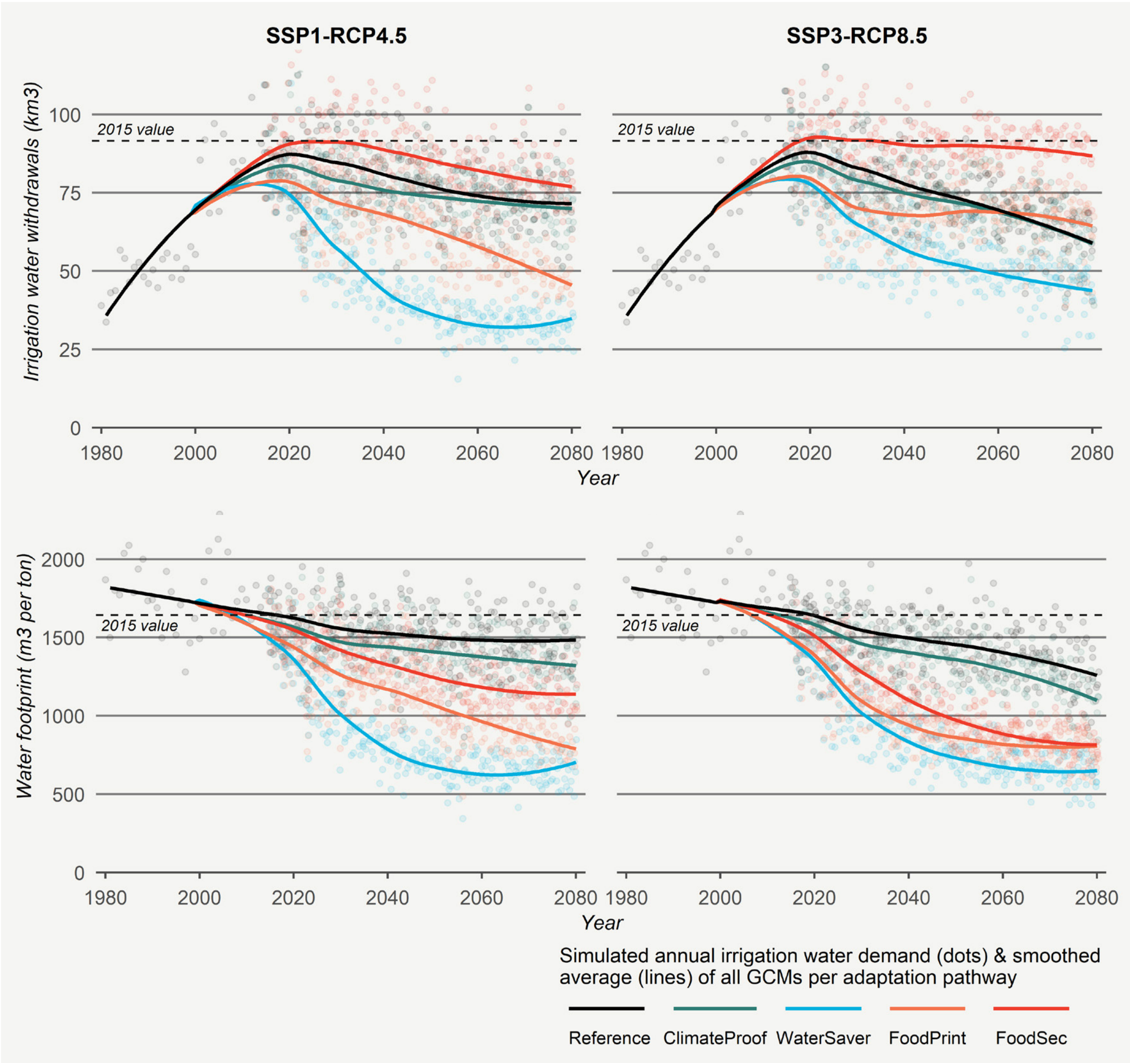


Figure 5.3: Historical water demand for irrigated wheat production (total water withdrawals, top, and per kg wheat, bottom) and projected water demand for the adaptation pathways. The dots represents the individual simulated water demand per year for each of the GCMs (i.e. four dots per pathway per year). The lines represents the smoothed average of all GCMs.

water demands in both scenarios is significantly stronger than the decrease wheat production. This means that the water footprint of irrigated wheat will decrease, especially in the SSP3-RCP8.5 scenario.

5.2.2. The cost of safeguarding future food security

The ClimateProof Pathways aim to mitigate the negative impact of climate change on wheat production with the fewest possible adaptation steps. Figure 5.4 demonstrates that in the SSP1-RCP4.5 scenario, this can be achieved with gradual production intensification until around 2050 in the regions of the Pakistani share of the basin that currently have the lowest yields (Appendix Figure D2).The population also stabilises by 2050, which ensures that climate change adaptation alone is enough in this scenario to maintain wheat production per capita above the 150kg threshold (Figure 5.2). To address the progressively severe climate impacts of SSP3-RCP8.5, the ClimateProof pathways require continuous adaptation steps throughout the entire projected period, including the widespread implementation of laser land levelling. Rapid population growth causes per capita wheat availability to nonetheless reduce below 150kg per capita by 2030. This indicates that ensuring future food security in the SSP3-RCP8.5 scenario requires more than climate change adaptation.

The other pathways aim beyond climate change adaptation and explicitly account for population changes. The primary goal of the FoodSec pathways is to sustain per capita wheat production at the current 200kg and retain the basin's position as a breadbasket that supports food security beyond its borders (Cheema & Qamar, 2019). Figure 5.5 shows that these pathways require significantly more extensive and immediate adaptation steps than the ClimateProof pathways to address the impact of both climate change and population growth. In the SSP3-RCP8.5 scenario, the FoodSec pathways can only sustain this adaptation process until 2060, at which point all adaptation options for the entire basin have been utilized (Figure 5. 4) and the 200kg per capita objective can no longer be met (Figure 5.2). Figure 5.3 shows that this will in addition require any future reductions in irrigation water demands from adaptation and climate change to be used for the expansion of irrigated wheat production. The FoodSec Pathways therefore do not achieve any irrigation water savings compared to the 2015 baseline in the SSP3-RCP8.5 scenario. Per capita wheat production does however remain above the 150kg threshold (Figure 5.2) by 2080. This suggests that the FoodSec pathways can ensure basin-level self-sufficiency is maintained. In the SSP1-RCP4.5 scenario, the 200kg per capita wheat production objective can be achieved with relatively few adaptation steps and only minimal additional irrigation water requirements compared to the Reference pathways (Figure 5.3).

5.2.3. Constraints for reconciling water-food adaptation

Rather than ensuring future food security, the priority of the WaterSaver pathways is to minimize irrigation water demands. The only adaptation options allowed to sustain wheat production above 150kg per capita are those that simultaneously improve the water footprint. Figure 5.5 demonstrates that these pathways initially opt for adaptation in the Indian Punjab, which is the most intensively cultivated area of the basin (Jain et al., 2017) and has the highest relative irrigation water demand (Appendix Figure D2). In the SSP1-RCP4.5 scenario, this approach can sustain wheat production at 150kg per capita (Figure 5.2) while reducing irrigation water demands by over 50% (Figure 5.3). Figure 5.4 shows that the reductions in irrigation water requirements are enhanced by increases in wheat production in the most water-efficient areas, which allow areas with lower water productivity to be withdrawn from

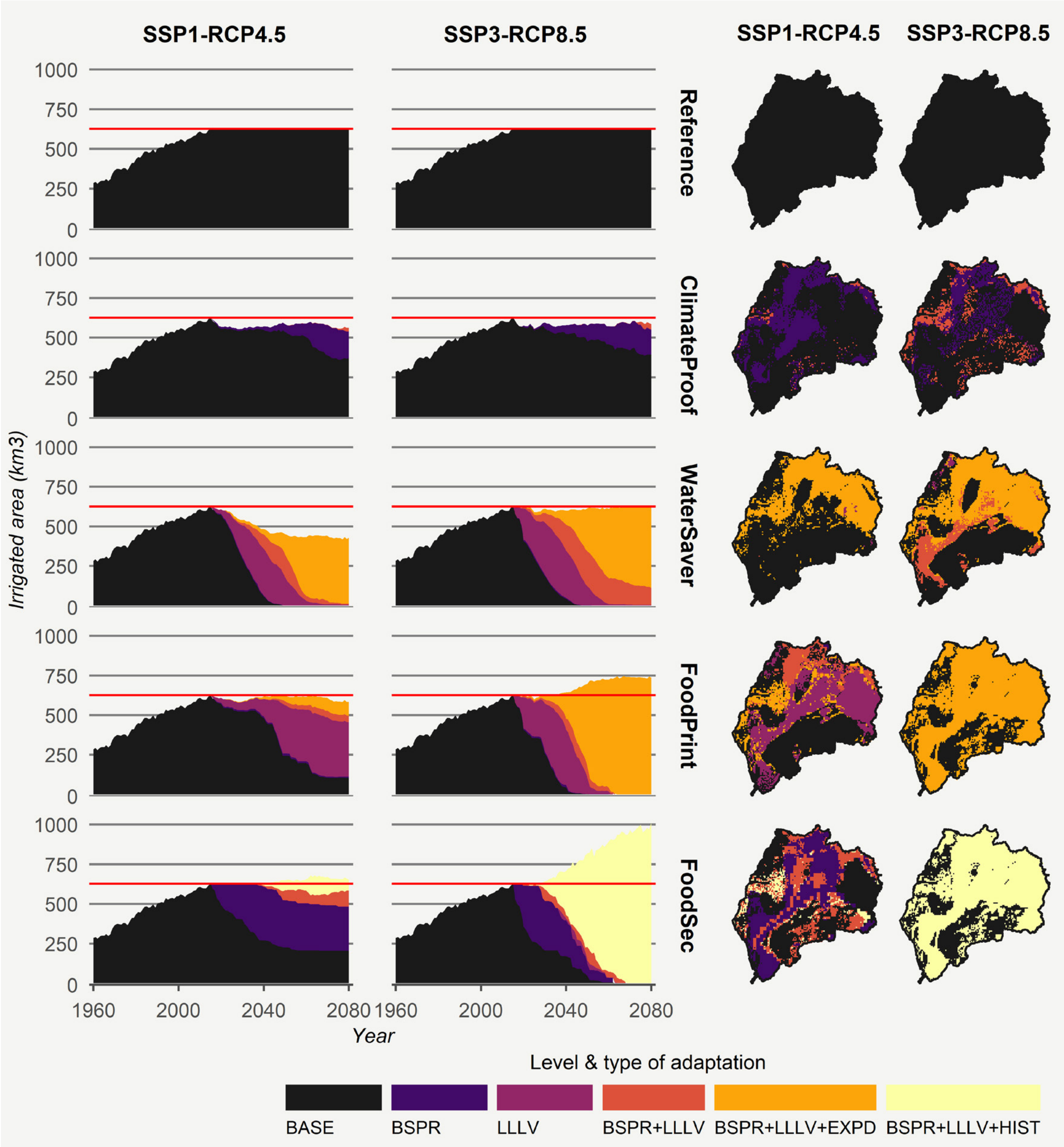


Figure 5.2: Total area of irrigated wheat under specific adaptation measures over the projected period for each of the adaptation pathways (average of all four GCMs). In addition, the maps illustrate the final adaptation map for each of the pathways in 2080, the end of the projected period (modus of the four GCMs for 2080).

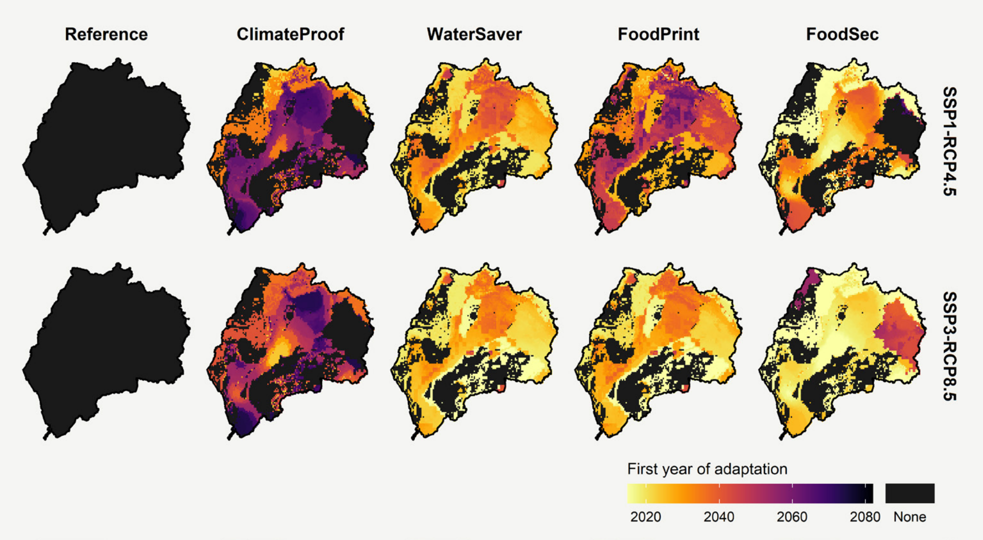


Figure 5.2: Year of first suggested adaptation action for each of the adaptation pathways (average of all four GCMs). Note that cells which were not adapted during pathways construction remain black.

production. This more than halves the water footprint of irrigated wheat at the basin level by 2080 compared to 2015. The WaterSaver pathways are however unable to achieve the 150kg per capita wheat threshold after 2050 in SSP3-RCP8.5 (Figure 5.2). Constraints on adaptation options that are not favourable for the water footprint mean that some adaptation options, such as production expansion, are not available in parts of the basin (Figure 5.4). This results in considerably lower adaptive capacity for food security compared to the FoodSec pathways. Nevertheless, Figure 5.3 shows that the WaterSaver pathways are the only pathways that significantly reduce irrigation water demands compared to the Reference pathways in the SSP3-RCP8.5 scenario.

The FoodPrint pathways similarly aim to minimize the water footprint of irrigated wheat production, but do allow some expansion of irrigated area as a last resort to option to ensure sufficient wheat production. Ample adaptation options are available in the SSP1-RCP4.5 scenario that can combine an increase in wheat production with reductions in irrigation water demands. Figure 5.4 shows that the adaptation steps of the FoodPrint pathways accordingly follow a similar trajectory to those of the WaterSaver pathways. However, in the SSP3-RCP8.5 scenario, these two pathways diverge after 2050 as the FoodPrint pathways ultimately take adaptation steps that are not beneficial to the water footprint to maintain per capita wheat production. As a result, irrigation water demands for the FoodPrint pathways decrease sharply on the short-term, but increase again after 2050 (Figure 5.3). Irrigation water demands by 2080 are nevertheless considerably lower than 2015 demands. The additional adaptation steps are shown in Figure 5.2 to allow the FoodPrint pathways to maintain wheat production at sufficient levels for a considerably longer period than the WaterSaver pathways. However, per capita wheat production still falls below 150kg by 2070. This illustrates that only the

FoodSec pathways can ensure future self-sufficiency for wheat production in the basin in the SSP3-RCP8.5 scenario.

5.3. Discussion

5.3.1. Implications for future water and food security in the Indus basin

The pathways of this study demonstrate that smart combinations of production intensification, laser land leveling and the targeted expansion of irrigated area can simultaneously increase wheat production and reduce irrigation water demands in the Indus basin. However, the extent to which adaptation for water (SDG6) and food (SDG2) security here can be reconciled on the long-term depends largely on the development of external drivers. For a future with severe climate change impact and continued population growth, mutually beneficial adaptation options alone are insufficient to sustain per capita wheat production. Pathways that prioritize food security therefore require adaptation that is nonbeneficial to the water footprint of irrigated wheat production, while pathways that aim to reduce irrigation water demand cannot meet minimum wheat production thresholds. In contrast, in a future with moderate climate change and population stabilization a range of adaptation objectives for SDG2 and SDG6 can be achieved. Pathways that address adaptation for both climate and population change from the outset in addition perform better for both objectives in the long run compared to those that focus solely on climate change adaptation.

An important methodological note is that the pathways approach used to obtain these findings is model-based and therefore inherently represent a simplified subset of the system of interest (Kwakkel et al., 2016). Our pathways approach considered three biophysical indicators, namely yield, water demand and sown area, to construct pathways for the Indus agricultural system. The sustainable management of these resources is a boundary conditions to achieve water, food and climate SDGs (Yillia, 2016). However, robust adaptation planning requires an understanding of how such factors interact with the broader decision making context (Werners et al., 2021). Our approach demonstrates if-and-how specific measures make wheat production more water-efficient, but does not consider for instance the cost of their implementation or upkeep, nor the required farmer knowledge. Whether the ensuing pathways present adaptation trade-offs worth making is thus determined by societal priorities- not only by the technical parameters and targets assessed in this study. Similarly, although the measures supplied to the algorithm are promising in terms of adaptation potential, myriad strategies exist which may offer complimentary effects (Smolenaars et al., 2023). The investigated measures are all technical interventions, which essentially optimize wheat production. The corresponding pathways thus fundamentally seek to preserve and strengthen the existing system of wheat production. Our results demonstrate however that maintaining this system may be challenging in an SSP3-RCP8.5 future. Subsequent studies should therefore look to complement our threshold-based pathways approach with transformation-oriented pathways approaches (Werners et al., 2021) that explore adaptation options for systemic change beyond technical optimization.

5.3.2. Benefits of spatial and multi-objective pathways for adaptation planning

The pathways constructed in his study are hence not directly actionable adaptation strategies. Nonetheless, they do illustrate the technical potential of the investigated adaptation measures to support varying compositions of water, food and climate SDGs under deep uncertainty. The identification of potential adaptation steps is made more substantial by the fact that our pathways approach is spatially explicit. The spatial dimension allows pathways to acknowledge that the suitability of adaptation measures is not distributed homogenously throughout the basin, but instead follows patterns in space which are determined by both local biophysical circumstances and the overarching objectives of adaptation. Despite being essentially regional in scope, our approach is thus able to include some diversity in local conditions in pathway construction, albeit only for factors that determine the technical fitness of specific measures. The approach developed in this study therefore provides an important step in bridging the scale gap between regional adaptation planning and the representation of local conditions, which constitutes a barrier for the policy relevance of pathways approaches (Cradock-Henry & Frame, 2021). For the Indus basin, this allows our pathways to consistently highlight an initial set of complementary actions that reduce the basin-level water footprint of irrigated wheat while increasing total production. Since the basin already faces severe water stress (Immerzeel et al., 2020) and increasing urban-rural competition over water resources (Flörke et al., 2018; Rasul, 2016), these localized adaptation steps provide a tangible premise for short-term action with limited risk of maladaptation.

Contrary to previous pathways assessments for wheat production (Tanaka et al., 2015), which focused solely on the uncertainty and impact of climate change on yield, our approach moreover accounted for the effect of population change in the development of pathways and explicitly introduced contesting constraints for water use. The ensuing pathways therefore provide insight into the interaction between multiple adaptation objectives and drivers on the long-term. This integration of climate change with societal development and SDGs addresses an important methodological advancement for the pathways learning goals formulated by Werners et al. (2021). Our approach finds similar results to Wijngaard et al. (2018) and Rasul (2016) in that population change, rather than climatic change, will likely be the dominant factor in adaptation for interlinked water and food security in the Indus basin. As forcing scenarios and corresponding pathways diverge, adaptation steps for the medium-to-long-term similarly become more ambiguous. In an SSP1-RCP4.5 future, continued adaptation is objective-dependent. Population stabilization ensures additional wheat production gains are not required for food security, but further measures may serve to reduce groundwater dependency (Salam et al., 2020), or provide space for other crops that are currently imported, like oilseeds and pulses (Kirby et al., 2017). Conversely, unabating pressure by drivers in SSP3-RCP8.5 demands continuous adaptation to meet wheat production thresholds and forces trade-offs between water and food objectives. These drivers moreover increase water demands for other societal purposes (Smolenaars et al., 2023). Adaptation strategies must therefore establish clear priorities, or pursue fundamental system changes.

The pathways approach developed in this study thus provides adaptation planning in the Indus basin with both robust options on the short-term and a flexible framework to evaluate long-term objectives for integrated water and food security. Our approach accordingly provides several important conceptual insights and methodological lessons for future pathway studies. Foremost, by dynamically integrating multiple drivers and objectives, our approach allows pathways to acknowledge trade-offs and dependencies that are crucial to account for in the development of holistic adaptation strategies. Furthermore, we demonstrate that adding a spatial dimension to pathways improves their capacity to consider for the variation in local conditions in adaptation planning for the regional level. These innovative features allow our pathways to capture how contesting objectives interact between the local and regional level and therefore to better represent the regional context in which adaptation occurs. Subsequent Indus basin studies could expand our approach to include the impact of socioeconomic changes on water-use sectors other than agriculture and introduce dynamic water security targets. This may enable pathways assessments to also explore consequences of adaptation changes for intersectoral water competition (Flörke et al., 2018) and upstream-downstream dependencies (Smolenaars et al., 2022). Our approach can moreover be applied for other regions where water and food security strongly interlink with climatic and socioeconomic changes. Contextually similar complex river basins where irrigation plays a strong role, such as the Nile, Ganges and Mekong (Johnston & Smakhtin, 2014; Siderius et al., 2022), may be of particular interest.

5.4. Materials and Methods

To construct adaptation pathways for the Indus basin we used a three step approach:

1. First, we used the LPJmL crop-hydrology model to make six datasets of spatial simulations for wheat yield and irrigation water demand. Each dataset accounts for climate change and considers a different combination of adaptation measures to be implemented throughout the entire Indus basin.
2. Then, we developed the Spatial Pathways Algorithm, which creates pathways that determine with annual timesteps the location and type of adaptation steps required to optimally achieve user-defined objectives for irrigation water savings and wheat production. The algorithm used the six simulated datasets to obtain spatial information on adaptation options for pathways construction.
3. Lastly, we applied the algorithm to construct pathways for five configurations of adaptation objectives and constraints, within the setting of two contrasting scenarios of future climatic and socio-economic change. Both scenarios contain four climate change models, meaning that a total 40 unique pathways were constructed.

5.4.1. Spatial simulations of wheat yield and irrigation water demand

Since the aim of our study is to develop adaptation pathways that include a spatial dimension, we required spatially explicit information on wheat yields and water demands in the Indus basin with and without adaptation. To obtain this data, we made spatial simulations of wheat production (rainfed and irrigated) and corresponding water requirements in the basin for historical conditions and under future climate change with various degrees of adaptation. The irrigation systems of the Indus basin, and hence virtually all irrigated wheat production, are located on the Indus plains (Portmann et al., 2010). We therefore focused our spatial simulations on the lower Indus basin (see Figure 5.1). Simulations were made at 5x5 arcmin resolution over the period 1950-2080 with daily timesteps, using a version of the LPJmL crop-hydrology model (Bondeau et al., 2007) that was adapted specifically to simulate water-food interactions in irrigation-dependent South Asian river basins (Biemans et al., 2019b). An elaborate model description can be found in Lutz et al. (2022). The model was calibrated to historical wheat yield statistics at the state (India) and provincial (Pakistan) level (see Figure D1 and Table D1) in the basin by Smolenaars et al. (2023).

Using this model setup, we first made simulations for two scenarios of climate change (see Table 5.2), each consisting of four downscaled GCMs (General Circulation Models) by Lutz, ter Maat, et al. (2016). We used spatially explicit historical land-use data for the Indus basin developed by Smolenaars et al. (2023) as input data to the LPJmL model. For the period 2016-2080, land-use was kept constant to 2015 conditions. This setup provided us with a dataset of baseline simulations of historical and future wheat production, and irrigation water demand under two scenarios of climate change, without considering for any land-use change or adaptation measures (see Figure D2). In addition to the no-adaptation baseline, we developed datasets in which adaptation does take place. Three distinct adaptation measures were considered: improved farm and crop management, laser land levelling, and the sustainable expansion of irrigated area. We made five spatial datasets of yield and irrigation water demand simulations which assume distinct combinations of these measures (i.e. adaptation options) are implemented in the entire basin. The following five datasets of adaptation options were developed with simulations for each climate model:

- **Best practices (BSPR):** farming systems in the basin intensify wheat production to the level currently seen in the Indian Punjab, which literature (Hussain et al., 2014; Jain et al., 2017; Khaliq et al., 2019) shows is close to the upper limit of yields that current farming systems in the region can attain through improved nutrient input and crop and water management, without requiring additional technical interventions. Although intensification may increase irrigation water demands, it will also strongly increase yields. These simulations were developed similarly to the original baseline simulation using LPJmL, but with farm management parameters across the basin set instead to value found after calibration (see Smolenaars et al. 2022) for the Indian Punjab.
- **Laser land levelling (LLLV):** the entire basin practices laser land levelling, a highly promising and relatively low-cost technique that allows water to be distributed equally throughout a field (Jamil et al., 2023). Precision levelling ensures uniform sub-surface infiltration, resulting in strong reductions in irrigation water demand and small, but significant, benefits for crop yield. To simulate the effect of his measure we corrected the baseline simulations to increase irrigated wheat yield and decreases irrigation water demand (i.e. without adaptation) with the values found by Jamil et al. (2023) for the Indus basin, based on the soil type in each respective cell. An overview of these values and a comparison to other studies can be found in Table A2.
- **Best practices & laser land levelling (BSPR+LLLV):** farming systems intensify to best practices and in addition employ laser land levelling. In this case, we applied values found by Jamil et al. (2023) to the wheat yield and irrigation water demand simulations of LPJmL with management parameters set to those of the Indian Punjab.
- **Best practices & Laser land levelling with sustainable expansion (BSPR+LLLV+EXPD):** farming systems in the basin shifts to best practices and implement laser land levelling. In addition, this adaptation option assumes that water saved through these adaptation changes may still be used at the farm-level. At the cell level, any reduction in irrigation water withdrawals in the simulations which account for both best practices and laser land levelling (in comparison to the baseline simulations without adaptation) may therefore be used to proportionally expand the irrigated area. Expansion is limited to cells equipped for irrigation and by the remaining area in each cell according to the MIRCA2000 spatial dataset (Portmann et al., 2010) updated to 2015 by Smolenaars et al. (2023).
- **Best practices & laser land levelling with sustainable expansion within historical water budget (BSPR+LLLV+HIST):** the entire basin shifts to best practices and employs laser land levelling. This option assumes that irrigation water allocation at farm level remains the same over the entire projected period, using the 2015 values as reference point. Grid cells with decreases in irrigation water demand, whether due to the effect of CO2 fertilization or the implementation of adaptation measures, may sustainably expand the irrigated area, up until irrigation water demand reaches the level of 2015. This expansion too is limited by the remaining area in each grid cell.

Table 5.1: Configurations of objectives and constraints for pathways construction.

Configuration Name	Objective	Constraints		
		Wheat yield	Irrigated area	Water budget
Reference	None	None	No change	None
ClimateProof	Mitigate the negative effect of climate change on wheat yield.	Maintain wheat production at 2015 levels.	No change	None
WaterSaver	Decrease the basin-level blue water footprint of irrigated wheat.	Maintain wheat production per capita at least at 150 kg per year.	Reduce as much as possible, prioritising cells with highest blue water footprint.	Decrease as much as possible at the basin-level. Demand in cells may increase only if it benefits the basin-level blue water footprint.
FoodPrint	Increase wheat production, if possible through measures that decrease the blue water footprint.	Maintain wheat production per capita at least at 175 kg per year.	Reduce if possible, sustainable expansion to limits of water budget if required to meet wheat target.	Demand in cells may not increase, but can use water may not exceed that of Reference baseline.
FoodSec	Produce as much wheat as possible.	Maintain wheat production per capita at least at 200 kg per year.	No reduction, sustainable expansion to limits of water budget if required to meet wheat target.	Grid-cell water demand may increase, but to expand the area, it may not exceed 2015 water demand.

Table 5.2: Overview of scenarios and scenario elements.

Name	Climate		Population (millions)				
	Type	Models	Type	2015	2030	2050	2080
RCP4.5-SSP1	Moderate	BNU-ESM CMCC-CMS CSIRO-Mk3-6 INMCM4	None	271	315	351	334
RCP8.5-SSP3	Extreme	BCC-CSM1-1 CANESM2 CMCC-CMS INMCM4	None	271	352	470	631

5.4.2. Spatial Pathways Algorithm

Secondly, we developed the *Spatial Pathways Algorithm* that creates, through space and time, adaptation maps that optimally achieve user-determined water and food security objectives. The algorithm operates under constraints imposed for the required wheat production, the total irrigated area and the total irrigation water demand. This approach is methodologically similar to previous threshold-based pathways approaches (Kingsborough et al., 2016; Kwakkel et al., 2016; Tanaka et al., 2015; Werners et al., 2021) that determine when a clearly-defined quantitative objective (i.e. threshold) will no longer be met and what adaptation steps are most suited to prevent this. However, our approach additionally considers each of the five adaptation options in each cell as a unique adaptation option towards achieving objectives at the basin-level. We therefore consider not only the 'when' and 'how' of adaptation planning, but also highlight the 'where' by adding an explicit spatial dimension to the pathways.

Specifically, the Spatial Pathways Algorithm shifts individual cells on a yearly basis between baseline conditions without adaptation, and the five different adaptation options described in the previous paragraph (see Figure 5.1). This process creates annual 'adaptation maps' which spatially demonstrate the adaptation steps that must be taken in any given year to achieve specific objectives. The algorithm takes the six spatial simulations of wheat yield and irrigation water demand as input data for the construction of adaptation maps. Each map, for each year, is therefore a combination between these six datasets and the water-use and yield values associated to them. Spatial adaptation pathways with yearly timesteps are formed by appending all annual maps into a series of adaptation steps. The algorithm starts in 2015 with all grid cells in baseline conditions (i.e. no adaptation and 2015 irrigated net sown area). For each subsequent year, the algorithm cycles through the following steps:

- First, the algorithm determines whether the wheat production threshold is likely be met in the upcoming year, and, if this is not the case, determines the expected production gap. To do so, the average total wheat production (irrigated and rainfed) for the preceding five years is determined under the latest adaptation map. The basin-level aggregated production is then compared to the production threshold for the subsequent year. If this threshold is not met, the difference between the expected production and the required production determines the production gap.
- If there is a projected production gap, the algorithm then determines for all grid cells how much wheat production and irrigation water demand would change in each cell if it were to shift to any of the other adaptation options, as compared to the values under its present adaptation status (see Figure 5.1, step 1). As there are a total of six adaptation options, this creates five potential changes per cell. For each cell, the most beneficial option is selected (see Figure 5.1, step 2). Depending on the objective of the adaptation run, this means either the option which demonstrates the largest reduction in water footprint (i.e. irrigation water used per unit of wheat produced), or the option which increases most the yield per unit area, is selected. Adaptation options which are not allowed due to the pathways constraints (e.g. increase in irrigation water demand) are eliminated. Given the same criteria used to select the best adaptation option per cell, all cells and their selected adaptation option are then sorted to create a cell-specific ranked list of adaptation options (see Figure 5.1, step 3).
- Based on this ranking, the algorithm iteratively selects the cell-based adaptation options, until the cumulative production increase in all of the newly adapted cells equals the production gap (see Figure 5.1, step 3). If there is no production gap, and the objective

of the run is to decrease the water footprint of irrigated wheat, adaptation options that bring about the strongest decrease of the basin-level water footprint are selected instead. The cells that are not chosen for implementation maintain the adaptation status of the previous year.
- If there is no production gap, but instead projected overproduction of wheat for the upcoming year, the algorithm will reduce the current irrigated area until the projected overproduction is eliminated, provided the pathways constraints allow such a change. The reduction of area takes a similar approach to the adaptation option selection step. Depending on the pathways objectives, cells are ranked either from largest to the smallest water footprint, or the lowest to highest yield per unit area. Based on this order, cells are then iteratively selected to be taken out of production, until the projected overproduction for the subsequent year is eliminated.
- Lastly, the changes are implemented to the present adaptation map, thereby forming the new adaptation map of the next year (see Figure 5.1, step 4). The updated adaptation map is appended to the series of previous adaptation maps to form the next set of steps in the adaptation pathways (see Figure 5.1, step 5).

5.4.3. Pathways objective setting and construction

To set the boundary conditions for our Spatial Pathways Algorithm, we established five different adaptation configurations (see Table 5.1). Each configuration consists of a primary objective, and of constraints for the desired wheat production, the total irrigated area and the irrigation water budget. These constraints provide the setting within which the Spatial Pathways Algorithm must develop an optimal pathways to achieve the objective using combinations of the five adaptation options. The configurations were designed to represent a range of different prioritisations and degrees of action for water use and wheat availability. The following five configurations were established:

- The **Reference** configuration assumes that no adaptation options are implemented in the Indus basin. Hence, the 2015 agricultural system is maintained over the entire projected period, regardless of the impact of climate change and population growth. This pathways is a 'baseline' to understand the consequences of not undertaking any adaptive action.
- The objective of the **ClimateProof** configuration is to mitigate the negative effect of climate change on wheat production as efficiently as possible. Adaptation steps are therefore only taken if required to maintain wheat production at 2015 levels under changing climatic conditions. This setup prioritises cell-specific adaptation options that demonstrate the largest increase in yield per unit area. The irrigated area may reduce if wheat production is projected to surpass 2015 levels, starting with areas with the lowest yield per unit area. Expansion of irrigated area is not allowed in this setup. No further constraints in terms of water use are considered.
- The **WaterSaver** configuration has the objective to reduce the basin-level water footprint of irrigated wheat as much as possible. An annual wheat production threshold of 150 kg per capita is maintained as a food security constraint (Zulfiqar & Hussain, 2014). This configuration prioritises adaptation options that decrease the water-use per unit area of cells. Adaptation options that increase irrigation water demand in a cell are not allowed, unless these increase the yield in the respective cell and its water footprint is below average. The subsequent yield increase in such high water-use efficiency cells may then be used to proportionally reduce the irrigated area in less water-efficient cells, thus improving the basin-level water footprint and reducing the area under irrigation. The total area under

irrigation may however not expand beyond the 2015 level, even if this means the wheat production threshold cannot be met.

- The objective of the **FoodPrint** configuration is to ensure sufficient wheat availability with the lowest possible water footprint. The wheat production threshold is therefore higher, at 175kg per capita per year, to maintain a buffer in case of unfavourable climatic conditions. Similar to the WaterSaver setup, adaptation options that are most beneficial to lowering the basin-level water footprint are prioritised. In case of projected overproduction, the irrigated area may reduce, starting with cells with low water productivity. However, this configuration does allow for the expansion of total irrigated area and the implementation of adaptation options that increase water demand if this is required to meet the wheat production threshold. Such adaptation options are implemented only after all adaptation options that do benefit the water footprint are exhausted.
- Lastly, the **FoodSec** configuration has the objective to ensure wheat self-sufficiency at all costs. The wheat production threshold remains at its current level of 200kg per capita per year (Smolenaars et al., 2023), thereby maintaining the position of the basin as a breadbasket for the region. This configuration prioritises adaptation options that increase the yield per unit area, regardless of its effect on irrigation water demand. The total irrigated area may not decrease, but expansion is allowed as long as irrigation water demand in a cell does not exceed the 2015 level.

Lastly, we applied the Spatial Pathways Algorithm for each of the five configurations under both climate change scenarios (RCP4.5 and RCP8.5, see section 5.2.1). The wheat production constraint of some configurations is additionally affected by population change. We therefore combined our climate change scenarios with population projections for the Indus basin by Smolenaars et al. (2021). These projections are regionally downscaled versions of the global Shared Socio-Economic Pathways (SSPs) and can therefore be consistently coupled with the RCP scenarios (O'Neill et al., 2014). We selected the Indus basin projections that correspond to SSP1 (population stabilisation) and SSP3 (continued strong population growth), as these are internally consistent with respectively the RCP4.5 and RCP8.5 (Riahi et al., 2017) climatic futures. The two integrated scenarios we used to force our pathways assessment therefore represent a 'best case' (RCP4.5-SSP1, hereafter SSP1) and 'worst case' (RCP8.5-SSP3, hereafter SSP3) outlook for the Indus basin (see Table 5.2). In the end, pathways were constructed for five adaptation configurations, under two integrated scenarios, each consisting of four climate models and one population projection. This means that we developed a total of 40 unique adaptation pathways.

Acknowledgements

Work of all the authors is supported by the SustainIndus project funded by NWO Wotro (Project W 07.30318.002), the Interdisciplinary Research and Education Fund (INREF) of Wageningen University and Research, and Utrecht University. HB would like to acknowledge partial funding from Wageningen University and the Food Security and Valuing Water research program supported by the Dutch Ministry of Agriculture, Nature and Food Security. SD acknowledges partially support by Sustainable Development Investment Portfolio (SDIP), the Department of Foreign Affairs and Trade (DFAT), Government of Australia, the Swiss Agency for Development and Cooperation (SDC) and by core funds from ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland and the United Kingdom.

The views and interpretations in this publication are those of the authors, and they are not necessarily attributable to their organizations.

6. Synthesis

Connecting the dots between water and food security, the SDGs and adaptation planning in the Indus basin

In this final chapter, the research of this thesis is placed in a broader societal and scientific context. First, the main findings for each research questions are summarized on the basis of the research chapters. The outcomes are then evaluated and reflected upon to address the main research objective. This information is used to draw important implications for adaptation policy making in support of the SDGs in the Indus basin and offers an outlook for future research on this topic. Next, the research approach used in this thesis is critically discussed in light of the methodological sub-objective, with a focus on the strengths and weaknesses of regional integrated modelling and the role of scenario building as a tool to manage uncertainties. The chapter concludes with an overview of the main conclusions and take-home messages.

6.1. Overview of study results in relation to research questions

Water and food security in the Indus basin are strongly interlinked and will face significant challenges in the future as a result of climate change and socioeconomic development (Basharat, 2019; Wijngaard et al., 2018). Adaptation strategies that account for interactions between water management and food production on the long-term are therefore urgently required to support SDGs for both water and food security (Wada et al., 2019). The development of such strategies requires adaptation planning to be informed by spatially explicit information on the potential effects of climatic and socioeconomic drivers, and adaptation strategies, on future water-food dynamics in the basin (Biemans & Siderius, 2019; J Liu et al., 2017; Rasul, 2016; Yillia, 2016). This thesis used a regional integrated modelling approach to explore how climatic and socioeconomic changes may shape the interaction between the water system and food production system of the Indus basin, and to examine how adaptation planning may address these changes to support sustainable long-term water management and food security objectives. The research work consisted of three sequential research steps that were addressed in Chapters 2 to 5. The steps first **identified drivers** of system changes (Chapter 2, 3, 4), then **defined trade-offs** that such drivers may incur for water and food security (Chapter 3, 4), and lastly **evaluated adaptation strategies** for their capacity to mutually support SDGs for water (SDG6) and food (SDG2) security (Chapter 4, 5). The following sections discuss the most important findings for the research questions associated with these steps.

6.1.1. How do socioeconomic and climatic drivers affect the supply and demand of water and food?

In the first research step, a scenarios analysis was used to study the individual and combined effects of various drivers on future water and food balances in the Indus basin. To this end, a novel approach was first developed in Chapter 2 to statistically downscale and regionalize socioeconomic projections from the global SSP framework (O'Neill et al., 2017). The projections were combined with climate data by Lutz, ter Maat, et al. (2016) to form a set of quantified scenarios that are specific to the Indus basin. The scenarios demonstrate that the plausible bandwidth of population growth in the basin, relative to the present ~270 million inhabitants, ranges from a stabilization around 320 million by 2050 to reaching over 620 million by 2080. Regional economic capacity will similarly at least triple, but up to tenfold increases are also possible in this period. These socioeconomic developments are strongly associated with increases in domestic and industrial water use (Bijl et al., 2016). Chapter 3 subsequently shows that socioeconomic drivers increase water consumption in the upper Indus basin between 88% and 146% by the 2060-2080 period. Domestic and industrial water demands in the lower Indus basin will similarly increase rapidly around major cities. The impact of these increases may however be partially moderated by climate change reducing agricultural water demands. Chapter 4 demonstrates that, for the current food production system, CO2 fertilization and shortening growing seasons reduce irrigation water demands for the Indus plains by up to 30% in 2080.

The reduction in irrigation water demand due to climate change is however associated with 15% to 20% decrease in food production in 2080 compared to the present. The current food production system therefore cannot meet future food demands in the basin for even low-range population projections. Chapter 4 demonstrates that if the food production system continues expanding along historical trends, total food production will increase, but still fall short of demands for higher-end future population estimates. This development would moreover considerably increase irrigation water demands. In conjunctions with increasing domestic and industrial demands, total water demands in the lower Indus basin subsequently increase between 11% and 28% in 2080 compared to 2015. The fulfillment of these demands strongly depends on surface water originating upstream. Future discharge projection for the upper Indus basin demonstrate total annual water availability and seasonal variability to increase under climate change (Wijngaard et al., 2017). Further analysis in Chapter 3 found these changes in discharge to strongly differ between subbasins and seasons. The Jhelum and Kabul subbasins were specifically identified as hotspots in the upper Indus basin where the future water availability per-capita will strongly decrease and increases in water consumption will exceed any gains in water availability. The increasing upstream claim on water resources diminishes dry season availability downstream, especially for the central Indus plains. This region does however contain rapidly expanding population centers and was demonstrated in Chapter 4 to account for a disproportionate share of increasing water demands in the lower Indus basin.

To conclude, this research step shows that climate change will negatively impact food production in the Indus basin, but does increase total annual discharges. However, any increases in water availability are far exceeded by rapidly growing water demands, predominantly for domestic and industrial purposes, brought on by socioeconomic changes. The upper Indus basin in particular faces a fast relative growth in water use and will require an increasing share of surface water originating here. Water stress throughout the basin is therefore projected to increase, but will intensify especially on the central Indus plains. This major agricultural region faces a strong surge in water demands for other sectors, and simultaneously sees water supply in the most critical dry season become less dependable due to the rapidly growing upstream claim and increased climatic variability. These changes may have critical consequences for the future availability of irrigation water required to meet growing food needs under population growth. Consistent with previous assessments (Immerzeel et al., 2020; Momblanch et al., 2019; Wijngaard et al., 2018), these findings therefore confirm that socioeconomic changes are likely the most important driver of the future water gap of the Indus basin. This research step in addition quantitatively highlights where such impacts should be expected and how they interlink with future food security. Subsequent studies that investigate climate change impacts on future agricultural water availability should therefore also consider how socioeconomic changes will drastically alter the amount and place in which water is needed for other sectors in the basin.

6.1.2. How may future trade-offs between water and food security develop?

The first research phase identified the effects of regional drivers on future supply-demand balances for water and food in the Indus basin. These drivers were further examined in the second research step by investigating how potential responses to their impacts may affect interactions and dependencies between water and food security. First, alternative strategies for agriculture development were defined in Chapter 4 and evaluated in relation to climatic and socioeconomic changes. The results primarily illustrate that the strong intensification and expansion of agriculture in the basin, in combination with a full shift to food crops, can ensure regional food self-sufficiency under climate change for the highest future population estimates. However, this strategy would increase irrigation water withdrawals in the basin up to 65% compared to the present. The increases in agricultural water demands are more prominent on the intensively cultivated Indus plains. This type of agricultural development strategy (i.e. expansion and intensification) will therefore compound the impact on water stress of rapidly growing water demands by the domestic and industrial sectors. Water use for urban purposes generally takes priority over rural purposes (Garrick et al., 2019). Simultaneous increases in water demands for domestic, industrial and agricultural purposes will therefore likely lead to increased intersectoral competition. This may inhibit the allocation of additional surface water for irrigation. Expansive agricultural development is consequently shown in Chapter 4 to increase the groundwater dependency of agriculture. This causes groundwater overextractions issues to expand throughout the basin and drives further infringements on downstream environmental flows.

Future agricultural development based on expansion in rainfed areas and a shift away from water-intensive crops is alternatively demonstrated to provide strong benefits for sustainable water management. This strategy reduces irrigation water demands sufficiently to compensate for growing demands in the industrial and domestic sectors, and halts the further expansion of groundwater use. Food production gains are however outpaced by all future population estimates. This type of sustainable development strategy for agriculture thus manages that water stress throughout the lower Indus basin will not increase further, but cannot ensure future food demands are met. The upper Indus basin was similarly shown in Chapter 3 to contain subbasins that will become increasingly water stressed and must modify water management practices to guarantee sufficient water availability throughout the year. Increased water storage for upstream use is often suggested as a suitable solution, due to synergies with hydropower for energy security (Dhaubanjar et al., 2021). However, results of the first research step showed that the expansion in water use in the upper Indus basin will substantially decrease downstream water availability in the dry season. Adaptive actions to facilitate or further expand upstream water-use activities will likely intensify such downstream impacts. The water supply from the upper to the lower Indus basin is in addition characterized by tense transboundary relations (Kalair et al., 2019). Changes required for water security in the upper Indus basin may affect cross-border water availability in regions that strongly depend on upstream water, and risk aggravating existing hydropolitical tensions.

In conclusion, this research step demonstrates that the pressure exerted by regional drivers, in particular population growth, will result in strong trade-offs between adaptation for water and food security in the Indus basin. Foremost, safeguarding food security on the basis of regional self-sufficiency requires the existing food production system to expand and intensify. The increases in irrigation water needed to sufficiently increase food production will however aggravate water security issues, such as water stress, intersectoral competition and unsustainable groundwater use in the lower Indus basin. Continued agricultural development in pursuit of food security therefore presents strong direct trade-offs with water security. This also threatens long-term water availability for food production, therefore affecting future food security too. These water scarcity issues are compounded by trade-offs between transboundary upstream and downstream water security interests, which may further reduce downstream water availability. Improving future water security throughout the basin therefore requires irrigation water demands to be brought into sustainable limits, and provide space to compensate for growing domestic and industrial water demands and less reliable upstream inflows. The basin-wide transition to a less water-intensive form of agriculture may strongly advance this objective. However, this does imply that a regionally self-sufficient food system might not be feasible in the future. These results illustrates that mutual progress for water and food security in the Indus basin ultimately exceeds the biophysical domain, as trade-offs between both objectives contain important economic, sociopolitical and transboundary aspects that must also be accounted for in integrated adaptation planning.

6.1.3. To what extent can adaptation of the food production system support the SDGs for both water and food security on the long-term?

The previous research step demonstrated that siloed adaptation strategies targeted at either water or food security may aggravate the challenges faced by the other respective objective. The final research step evaluated the degree to which optimized combinations between different strategies can instead provide a unified response to support the corresponding SDGs on the long-term. The key focus for this assessment was the food production system, which due to its vast irrigation water demands forms the main connection between water and food security in the Indus basin (Rasul, 2016). The agricultural development strategies of Chapter 4 were therefore investigated further. The previous research step found that these strategies may cause considerable trade-offs between basin-level water and food security objectives. However, additional subregional analysis also revealed potential shared benefits. Primarily, food production gains under the agricultural expansion and intensification strategy markedly exceed the corresponding increases in irrigation water demands. This means that, although total agricultural water use increases, the overall water-use efficiency improves. The strategy focused on sustainable agricultural water management was instead shown to achieve substantial irrigation water savings alongside a slight increase in food production in predominantly rainfed areas. Chapter 4 demonstrated that changes in the balance between food production and irrigation water demands for the different agricultural development strategies are moreover highly heterogenous in terms of their spatial distribution throughout the basin. This suggests that combinations between these strategies could mitigate the downsides of both approaches and potentially ensure benefits for water and food security at the basin-level.

Adaptation pathways were used in Chapter 5 to better understand how agricultural development may be coordinated for integrated adaptation towards SDG2 and SDG6. The pathways assessments focused specifically on the relation between the future self-sufficiency for wheat, a key food security indicator, and irrigation water demands. First, the basin-wide changes of the agricultural development strategies of Chapter 4 were broken down into manifold independent changes at the grid-cell level. This information was combined with data on the technical potential of laser land leveling (Jamil et al., 2023) to create a spatial dataset of adaptation options. These cell-based options were then iteratively combined through time into pathways using a novel spatial pathways tool. Pathways were constructed for different prioritizations between future wheat production and irrigation water savings and evaluated in Chapter 5 against the drivers of regional change. This demonstrated that the impact of climate change on total wheat production can be moderated through expansion and intensification in the most productive zones of the basin, in combination with water savings in less productive zones. However, counteracting the impact of population growth on future wheat production targets was found to be more challenging. For the highest population projections, pathways lack capacity to ensure wheat production remains at current per-capita levels even when allocating all irrigation water savings for further production expansion. Pathways that prioritize food security accordingly do not ensure any water savings, while those that focus at water security do not meet minimum wheat production thresholds.

This final research step therefore concludes that modifications to the food production system are a crucial tool for integrated adaptation planning to support SDG2 and SDG6 in the Indus basin. The appropriate design, location and timing of such changes is however challenging due to the high uncertainty of climatic and socioeconomic changes. Basin-wide agricultural

Table 6.1: overview of main findings and conclusions of this thesis for the research question and both objectives.

Research question	Main findings and conclusions
How do socioeconomic and climatic drivers affect the supply and demand of water and food?	• Socioeconomic changes will strongly increase the total demand for water and food in the basin, and cause the geographical location in which these demands occur to concentrate around major cities (Chapter 2). • Fast increasing water consumption due to socioeconomic changes means that some upper Indus subbasins may face future water stress, despite increases in mean annual discharges due to climate change (Chapter 3). • Expanding water consumption in the upper Indus basin likely decreases future downstream water availability in the dry season. (Chapter 3). • Climate change will decrease output of the current food production system, while demand will increase fast with population growth (Chapter 4). • The combined effects of socioeconomic and climatic change will likely strongly exacerbate water stress on the Indus plains (Chapter 2, 3 & 4).
How may future trade-offs between water and food security develop?	• Water management changes (i.e. storage dams) may be needed to ensure water security in the upper Indus basin, but can affect water security downstream and further aggravate transboundary tensions (Chapter 3). • Domestic and industrial water demands will likely grow faster than irrigation water demands, increasing intersectoral competition (Chapter 4). • Agricultural development based on the intensification and expansion of the food production system strongly aggravates water stress (Chapter 4). • The further expansion of irrigated agriculture makes food production more dependent on unsustainable groundwater resources (Chapter 4). • Agricultural development which prioritizes reducing water stress may inhibit maintaining self-sufficiency for food production (Chapter 4).
To what extent can adaptation of the food production system support the SDGs for both water and food security on the long-term?	• Changes to the food production system can ensure benefits for future water and/or food security, but are marked by strong trade-offs (Chapter 4). • Spatial adaptation pathways can balance trade-offs and benefits between water savings and gains in wheat production at the basin-level (Chapter 5).

Research objectives	Main outcomes
To quantitatively explore how water management and food production in the Indus basin can be adapted to support both water and food security related Sustainable Development Goals in the face of climatic and socioeconomic changes.	• The technical adaptation of food production and water management practices in the basin is a powerful tool to benefit both water and food security objectives and respectively SDG2 and SDG6. • Targeted technical optimization provides sufficient adaptive capacity to ensure mutual progress for SDG2 and SDG6 in futures with moderate population growth and climate change, but cannot support both objectives on the long-term with high population growth and severe climate change. • Adaptation planning for water and food security in the Indus basin must account for trade-offs and synergies with societal developments related to other SDGs, such as hydropower and sustainable economic expansion. • An integrated and transboundary river basin management plan for the Indus basin may be needed that goes beyond water and food links.
To draw methodological lessons for quantitative assessments in support of the Sustainable Development Goals in regions with strong water-food interactions.	• Regionally specific scenarios are key to provide models with suitable design criteria and input data, and with context to interpret implications for SDGs. • The SSPs are a valuable source for quantified scenario-based projections, but require regionalization and spatialization for use in regional modelling. • Complex process-based models are strongly complemented by conceptual models that allow larger regional trends to be assessed more transparently. • Spatial adaptation pathways are a suitable approach to design actionable steps at regional scale for integrated water-food adaptation and the SDGs.

development strategies can consequently amplify trade-offs between water and food security, and may lead to maladaptation. The adaptation pathways approach instead balances both objectives stepwise alongside the development of specific drivers. Pathways are subsequently able to provide flexible adaptation strategies that realize substantial shared benefits for the associated SDGs. However, for high-end future population estimates, pathways do ultimately run out of mutually beneficial adaptation options and are forced to prioritize either food production increases or water savings. This suggests that adaptation strategies targeted at the food production system can enable substantial integrated progress towards both water and food security related SDGs, but that biophysical limits may exist for the reconciliation of food self-sufficiency and sustainable water management under continued population growth. Adaptation planning in the Indus basin must therefore take into account that, even with far-reaching adaptation efforts, current system dynamics and contesting objectives may not be tenable on the long-term. This requires clear visions and priorities to be established on the position of the food production system for future food security and water management in relation to the SDGs. In addition, the anticipatory exploration of more radical options for systemic changes may ultimately be required.

6.2. Implications for adaptation planning to achieve SDGs in the Indus basin

The findings and conclusions for the three research questions (see Table 6.1) provide a basis for the main research objective of this thesis to be addressed. The following sections therefore first draw a succinct conclusion with respect to the main research objective, and then reflect further on the meaning of these findings for policy making towards achieving the SDGs in the Indus basin. The chapter ends with a set of recommendations and implications for adaptation strategies in the basin and for future research.

6.2.1. Conclusions: adaptation of food production and water management

This thesis aimed to quantitatively explore how water management and food production in the Indus basin can be adapted to support SDGs for both water (SDG6) and food (SDG2) security in the face of climatic and socioeconomic changes. With respect to this objective, climatic and socioeconomic drivers were shown to be highly uncertain, but increase pressure on water-food relations in all plausible futures. Integrated progress for SDG2 and SDG6 therefore requires the vast irrigation water demands to be reduced to sustainable limits and compensate for other expanding water-use sectors in the lower Indus basin, without jeopardizing future food production, and in coordination with water management changes in the upper Indus basin to avoid upstream-downstream conflicts. The type and degree of adaptation required to achieve these objectives depends strongly on the drivers. For moderate population growth and climate change, a combination of targeted agricultural development and technical innovations is shown to reconcile self-sufficiency for staple crops with sustainable water management. However, under continued rapid population growth, strong increases in demands for both water and food considerably intensify competition for water resources between food production and other sectors, and between the upstream and downstream. The subsequent trade-offs between water and food security cannot be mitigated even with basin-wide technical interventions, indicating that the current system may be untenable. This suggests adaptation planning in the basin must also look for alternative pathways and reconsider current paradigms for water and food security, based on a critical reflection on the SDGs.

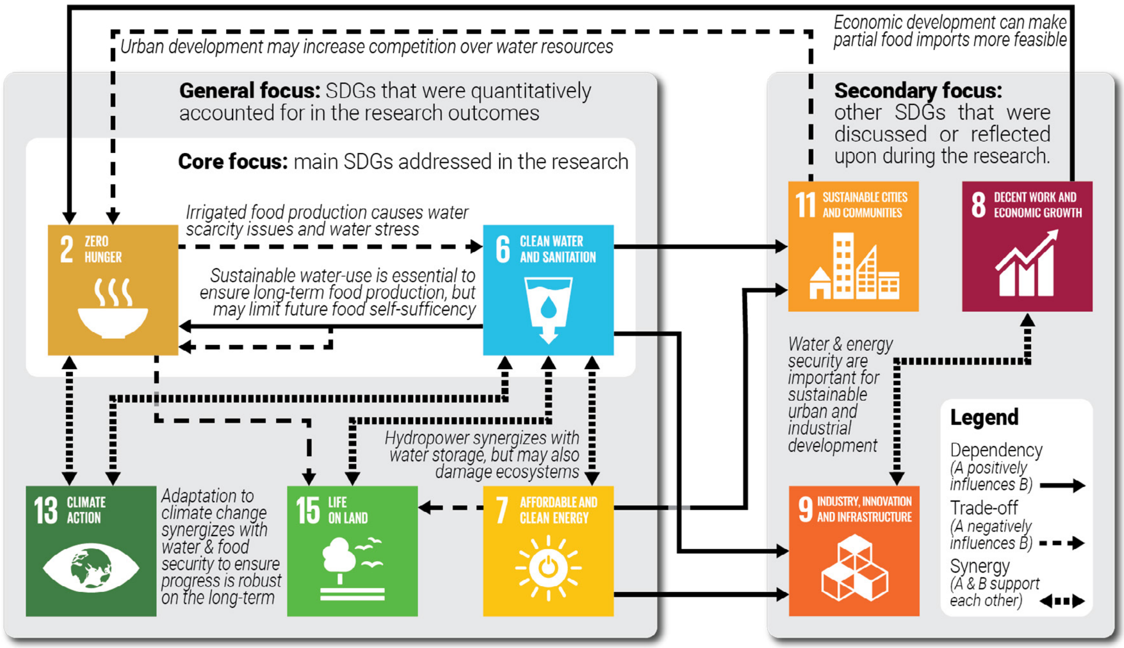


Figure 5.2: Overview of dependencies, trade-offs and synergies between the SDGs that were addressed or discussed in this thesis. The left panel highlights SDGs that were directly studied during the research step. This largely revolves around the interactions between SDG2 and SDG6, and the consequences for, or linkages with, other SDGs such as SDG7, SDG13 and SDG15. The SDGs in the right panel are other SDGs that were not directly part of the research approach, but instead were found during reflection on the research outcomes to have important linkages to water and food security. The linkages with these SDGs are crucial to better understand some of the interactions between water and food security and the dependencies that determine the feasibility of adaptation strategies.

6.2.2. Challenges and alternative pathways for water and food security

The most important future challenge for achieving SDG2 and SDG6 in the Indus basin is managing the trade-offs that result from simultaneously satisfying the rapidly rising demands for both water and food. From the perspective of food security, it is incontestable that more food is required in the future due to population growth. However, the translation of growing food demands into increasing pressure on the water system, and thus trade-offs, is based on the policy position that these demands must be met by local production. Self-sufficiency is a pillar for food security as it modulates food prices and ensure stable access for the most vulnerable groups (Clapp, 2017), and is politically important because it lessens dependencies in light of the tense relations between the riparian states (Baer-Nawrocka & Sadowski, 2019; Bishwajit et al., 2013). Nevertheless, at the basin-level, water supply ultimately poses a fundamental limit to which sustainable water use must adhere, while food demands can be met through imports. Shifting away from export and water-intensive crops, such as cotton and sugarcane, and partially relying on partial imports may therefore prove crucial to break away from the intensifying trade-offs between water and food security. However, this may upset trade balances, requiring the expansion of other economic activities in compensation. In this light, industrial products offer a significantly higher water productivity than agriculture (FAO, 2018). Industrial expansion in large parts of the basin is currently constrained by inadequate water availability and limited energy security (Rasul, 2016; Young et al., 2019).

Previous studies (Dhaubanjar et al., 2021; Janjua et al., 2021; Molden et al., 2014), and this thesis alike (Chapter 3), accordingly suggested that capitalizing on the vast hydropower potential of the upper Indus basin provides multiple benefits. Foremost, hydropower supports economic development in the basin by improving energy production and reducing the need for oil imports, which are currently a massive burden on regional trade-balances (Janjua et al., 2021). Hydropower additionally often relies on storage dams. Increased storage capacity may allow more modulation of water between seasons, which can increase water availability when it is most needed and moderate discharge extremes (Rasul et al., 2021). Managed groundwater recharge similarly holds potential to leverage wet season surpluses for dry season use (Lytton et al., 2021). However, these interventions essentially modify annual water availability through time to optimize its use, and thus increase the water claim of regions they are implemented for. This may have downstream impacts, especially as hydropower potential is largely located in transboundary zones (Dhaubanjar et al., 2021). Such approaches must therefore be accompanied by comprehensive upstream-downstream coordination to ensure basin-wide benefits (Basharat, 2019). Similarly, the political shift away from self-sufficient agriculture towards more economically optimized water allocation can realistically only occur when economic interests supersede those of national security, and thus requires cooperative riparian relations. However, the climatic and socioeconomic drivers that may require such drastic economic transitions are shown in this thesis to also increase transboundary upstream-downstream water competition, which can intensify hydropolitical tensions in the basin.

6.2.3. Towards integrated adaptation beyond the SDGs for water and food security

The research outcomes of this thesis highlight that transboundary and intersectoral cooperation are not just a more cost-optimal approach to achieve SDGs, as demonstrated by Vinca et al. (2020), but may in certain situations also form a fundamental boundary condition for integrated water-food adaptation in the Indus basin. Sustainable adaptation planning must therefore be based on a holistic understanding of linkages between SDGs and transboundary interests throughout the basin (Wada et al., 2019). This thesis deepened the quantitative knowledge on how SDGs for water (SDG6) and food (SDG2) security may interact in the future, with links to climate action (SDG13) and freshwater ecosystem health (SDG15), but also identified economic and political processes related to other SDGs that may obstruct or enhance potential adaptation strategies. Subsequent research may therefore expand beyond the water-food scope to also explore linkages with other SDGs. Foremost, energy security (SDG7) provides strong synergies with water and food security, but requires careful transboundary coordination. Extending the regional modelling approach used in this study to encompass the full water-food-energy nexus is therefore a logical first step. The integration of trade-flows into this nexus (Pastor et al., 2019) may similarly clarify links between water allocation and agriculture for economic development (SDG8 & SDG9) in relation to the world outside the basin. Lastly, more detailed spatial information is required on how sustainable urban expansion (SDG11) in the basin can be guided to mitigate negative impacts on future water and land availability for agriculture (Rasul, 2016) and for upstream-downstream dependencies.

This network of interdependencies between SDGs in the Indus basin (see Figure 6.1) led numerous previous studies to suggest that, rather than further technological fixes, a comprehensive river basin management plan for sustainable development first needs to be established (Kalair et al., 2019; Laghari et al., 2012; Rasul et al., 2021; Wada et al., 2019). This thesis shows that large-scale modifications of food production and associated water management are powerful adaptation mechanisms to support SDGs for water and food security. Their design must however be embedded in broader adaptation strategies that also account for SDGs related to other environmental and socioeconomic factors, and that balance upstream and downstream interests. Besides sound scientific knowledge, the development of integrated strategies at the basin level additionally requires trust and cooperation between riparian states (Rasul et al., 2021). In this light, the 1960 Indus Water Treaty already provides a framework for transboundary water allocation with a legacy of trust-building and conflict resolution (Zawahri & Michel, 2018). There are however increasing calls that the treaty must be revised to better address the impact of climate change and increasingly more complex linkages between environmental flows, food production, hydropower and economic development (Qamar et al., 2019; Sarfraz, 2013; Zawahri & Michel, 2018). This renegotiation process may provide an opportunity to solidify the SDGs as shared objectives for transboundary cooperation into an 'Indus Sustainable Development Treaty' that can provide a benchmark for future adaptation. Research on how to overcome political barriers for such joint development is therefore required.

6.3. Methodological advances, limitations and lessons

Besides the scientific outcomes presented in the previous sections, this thesis also produced several methodological advances with respect to the quantitative analysis of linkages and adaptation strategies for water and food security. These advances were developed specifically for the Indus basin, but may be relevant for other places in the world with similar challenges as well. The secondary research objective of this thesis was therefore *to draw methodological lessons for quantitative assessments in support of the SDGs in regions with strong water-food interactions*. This methodological objective is addressed in the following sections with an in-depth reflection on the regional integrated modelling approach, and on the role of scenarios and indicators for the policy-relevance of such modelling approaches. The insights gathered through these reflections are finally collected in a succinct overview (see also Table 6.1) of the most important methodological advances and lessons provided by this thesis.

6.3.1. Balancing complexity and transparency in regional integrated modelling

The linkages between hydrology, irrigation and food production in the Indus basin are relatively unique. To better understand how climatic and socioeconomic changes may influence these linkages, the modelling approach of this thesis was specifically designed to fit the regional context. The main modelling tool consisted of a version of the LPJmL crop-hydrology model that was developed by Biemans et al. (2019b) to better simulate spatiotemporal dynamics for irrigated agriculture in South Asia. This model version represents the double cropping systems that are prevalent on the Indus plains (Kirby et al., 2017), and includes modules for reservoirs and irrigation command areas to comprehensively simulate irrigation water supply. The accurate representation of regional irrigation dynamics proved highly advantageous, especially in Chapter 4, to obtain a detailed understanding on places and times where changes to irrigated agriculture will likely aggravate water scarcity, or may instead provide opportunities due to shifts in water availability. The LPJmL model does however lack a detailed groundwater module. Groundwater is therefore portrayed in this thesis as a cell-specific infinite source of water without lateral flows. This allowed structural overextraction and depletion to be determined, but did not represent the feedbacks between dropping groundwater tables and limitations on its availability for irrigation, which are already a considerable issue in the basin (Salam et al., 2020). Therefore, future studies may spatially disentangle the dependencies and use of groundwater in the Indus basin, in similar fashion to the assessment by Biemans et al. (2019b) on meltwater contribution to agriculture.

A more fundamental blind-spot in the modelling approach of this thesis is that the water security implications of changes in food production focused exclusively on water quantity issues. The primary reason for this is that the LPJmL model does not consider for nutrient availability in the crop growth module, using a more simplified comprehensive management parameter instead (Bondeau et al., 2007). Model simulations for agricultural changes, such as intensification in Chapter 4 and 5, accordingly assessed hydrological consequences, but did not provide information on potential exchanges of nutrients from land to surface water. Nutrient pollution from agriculture does however have considerable effects on the quantity of water that is actually fit for societal use in South Asia (Shahbaz & Boz, 2022; Strokal et al., 2019). The outputs of other crop-hydrology models that do represent nutrient management have been coupled with water quality model to assess how food production increases may affect downstream water quality in China (Chen et al., 2020; Droppers et al., 2022). This type of assessment is an important next step for the Indus basin to further explore how upstream-downstream linkages between SDGs for food security (SDG2), and water security (SDG6) and freshwater ecosystem health (SDG15) may develop. Future model development may additionally look for a two-way coupling between crop-hydrology and water quality models. This would allow potential feedbacks between the effect of agriculture on water quality, and the downstream consequences of such water quality impacts for agricultural productivity, to be mapped as well.

The inclusion of groundwater and water quality factors in the LPJmL model would further increase model complexity. This is associated with a decrease in transparency of model outcomes (Paola & Leeder, 2011). However, some research objectives instead required an emphasis on simplicity in the modelling approach design. The upstream-downstream assessment of Chapter 3 could, for instance, have been performed with the LPJmL model as well, but any effects of the relatively small upstream changes would be hard to identify within the full complexity of other model processes and design assumptions that simultaneously affect discharges across the basin. Therefore, a water accounting framework at subbasin level was developed on top of LPJmL data that focusses only on the fundamental components of upstream-downstream linkages. This allowed the transparent and flexible assessment of the role of drivers for upstream water use and downstream water availability, providing an initial spatialized overview of key trends. Similarly, an external module was developed in Chapter 5 to construct spatial adaptation pathways, using simulations of wheat production and irrigation water demand from multiple LPJmL runs. The evaluation of adaptation strategies is also possible through the LPJmL model itself and can account for many more environmental variables (Jägermeyr et al., 2021). However, such simulations only assess the suitability of predetermined strategies, providing limited insight into the design process that ultimately inform adaptation planning. The simple pathway design instead allowed links between drivers, objectives and ensuing strategies to be made explicit and subsequently translated into actionable adaptation steps.

These model design choices, both in terms of increasing the complexity of the LPJmL model and the development of simpler alternatives, demonstrate different sides of a fundamental dilemma for integrated modelling approaches. Environmental systems are ultimately too complex to fully model, but the appropriate level of complexity required to adequately represent these systems depends strongly on the information needs that the model must address (Hibbard & Janetos, 2013). Complex models can more accurately represent responses to drivers and are therefore better able to predict future systems, while simpler models make relations between system processes and outcomes transparent and accordingly have higher explanatory capacity (Paola & Leeder, 2011). This thesis demonstrates that fully distributed crop-hydrology models, such as the LPJmL model in Chapter 4, are well suited to help understand the magnitude and location of potential consequences for water and food security that may arise from the interplay of numerous developments. Yet, this same complexity and high level of detail also limits the capacity of such models to explain how such impacts come about, especially in relation to multiple uncertain drivers. The detailed representation of water-food interactions is therefore important, but must not obscure the more abstract 'bigger picture' of developments at the basin-level. Simpler conceptual models focused more at the system processes were accordingly shown in Chapter 3 and 5 to be highly complementary to the complex LPJmL model, by providing more transparent and exploratory overviews of trends and spatial hotspots in the basin for a broad range of drivers.

6.3.2. The crucial role of regional, quantitative and spatial scenarios

The value of model outcomes depends strongly on the quality of input data. Since the temporal scope of this thesis predominantly focused on the future, model inputs could not be derived from observational data. The long-term development of socioeconomic and climatic drivers that were accounted for in the modelling process is however extremely complex, and partially determined by societal choices in the present. An often used approach to gather model input data for such highly uncertain drivers is to use prescriptive forcing scenarios (Rounsevell & Metzger, 2010). Rather than trying to 'predict' how drivers may develop, prescriptive scenarios revolve around hypothetical 'what-if' narratives that describe the general direction of interlinked climatic and socioeconomic developments. These qualitative storylines provide context to make internally consistent assumptions about the future of more specific drivers and factors, such as potential land-use changes or water management choices, that can be quantified to serve as model input data. This implies that the suitability of input data is strongly influenced by the relevance of the scenario narratives. Previous water-food modelling studies for the Indus basin (Vinca et al., 2020; Wijngaard et al., 2018) sourced input data from scenarios based on the Shared Socioeconomic Pathways (SSP) framework and associated climate change projections (Riahi et al., 2017). The SSPs storylines are however designed for the global level and subsequent data products may not represent the unique development challenges of the Indus basin. In this thesis, regionalized scenarios that were designed specifically for the Indus basin were therefore used instead.

The core of the Indus basin scenarios was developed in Chapter 2 by coupling a set of qualitative narratives for future development in the South Asia region by Roy et al. (2019) to the global SSP storylines. This combination allowed the quantitative long-term socioeconomic projections pertaining to the SSPs to be adjusted and statistically downscaled to align with the regional context. The detailed regional narratives in addition allowed other scenario elements and downscaled climate change projections (Lutz, ter Maat, et al., 2016) to be consistently appended to the scenarios. This proved essential to fully utilize the potential of the modelling tools, as it allowed highly specific regional developments at the core of the adaptation discourse in the basin, such as the agricultural trajectories of Chapter 4, to be flexibly contextualized, simulated and quantitatively explored. An important obstacle for the link between model and scenario is that scenario elements ultimately must be expressed in spatially quantified data to serve as input for fully distributed models. In Chapter 2, a tool to simulate future population distributions was therefore developed. This provided a crucial base-layer to spatialize other scenario elements into model inputs throughout this thesis, such as domestic water demands. The narratives for the agricultural development strategies of Chapter 4 were however spatialized through linear extrapolation of the existing cropped areas. More research is therefore needed on how to quantify and spatialize regional scenarios for use in integrated models, while ensuring their contextual richness and nuance is preserved in the model outcomes.

6.3.3. Selecting and developing suitable indicators for water and food security

Translating model outcomes into information that helps to better understand SDGs for water and food security required the use of indicators. The LPJmL model used in this thesis largely provided spatial data on biophysical variables such as discharge, water use and yields. The combination of these model outcomes with quantitative scenario elements (e.g. population projections) subsequently allowed indicators of water and food security to be established that focus predominantly on the sufficient availability of both resources. Food security, for instance, was determined by the food self-sufficient ratio (Clapp, 2017), simulating the degree to which regional food production can meet future food needs. Similarly, the water stress and environmental flow indicators used to operationalize water security essentially determine whether sufficient water is available in the future for respectively society and ecosystems (Falkenmark et al., 2009; Pastor et al., 2014). Although these indicators represent some of the most important policy dilemmas for the SDGs in the basin (Rasul, 2016), water and food security are far more complex and multidimensional than ensuring sufficient availability of both resources. In addition to being available, these resources must also be accessible and of sufficient quality for human use (McNeill et al., 2017; UN, 2015a). However, these security dimensions exceed the biophysical scope of the LPJmL model and moreover largely manifest at household level. Subsequent studies may therefore provide qualitative reflection, preferably alongside the perspectives of regional policy makers, on the relation between availability changes found in this study and other dimensions of water and food security.

The indicators used in this study moreover demonstrate the benefits, and limitations, of using different spatial scales to assess water and food security implications. The high spatial resolution LPJmL model outcomes allowed processes like future crop losses and groundwater overextractions to be determined at essentially the local level. Such processes are strongly associated with negative consequences for water and food security, and the detailed insights in Chapter 4 on where they should be anticipated is important for adaptation planning (Yillia, 2016). However, this information ultimately only addresses biophysical impacts and does not translate into direct societal implications, meaning these are indicators for, rather than of, water and food security. The beforementioned availability indicators instead do explicitly demonstrate impacts on society, but are accordingly studied largely at system level, rather than locally (Baer-Nawrocka & Sadowski, 2019; Hanasaki et al., 2018). The detailed LPJmL simulation were therefore aggregated to coarser subbasin levels in Chapter 3 and 4 to assess these indicators, which allowed the broader regional patterns for water and food security in the basin to be established. Similarly, the adaptation pathways of Chapter 5 define cell-level adaptation steps, but these all pursue unified objectives for the basin. Although local biophysical conditions are thus accounted for, local water and food security goals are not. Future studies should therefore design indicators that can also demonstrate societal water and food security implications beyond the system level, as this allows the high-resolution outputs of distributed crop-hydrology models, such as LPJmL, to be utilized better.

6.3.4. Methodological lessons from the Indus basin for similar studies in other regions

The results of this thesis allowed for a detailed and regionally specific understanding of future challenges and strategies for the SDGs related to water and food security in the Indus basin. An important methodological takeaway is that these results were largely realized on the basis of strong synergies between quantitative modelling approaches and regionally specific scenarios. Distributed crop-hydrology model are highly complex, especially at the regional level (Vinca et al., 2021), and require clear modelling objectives and corresponding input data for the regional changes that are investigated. This thesis demonstrated that scenarios with intricate storylines on plausible regional futures can provide a contextual basis for such design decisions and ensure the modelling process targets future developments that are relevant to regional adaptation planning. However, translating the qualitative core of scenarios into model input requires the addition of spatially quantified scenario elements. The global SSP projections (Riahi et al., 2017) proved to be an important starting point for such data, but first need adjustment and downscaling to the regional context, for which a step-by-step methodology was presented in Chapter 2. The quantified scenario elements were moreover proven to combine well with biophysical model outputs and help understand their societal implications. This highlights that for regional water-food assessments, scenarios are more than a tool to gather input data in service of models, but can, if purposefully designed, also be a qualitative source of regional context that is essential to guide the modelling process and reflect on its outcomes for the SDGs.

In addition, several simple spatial modelling tools that target specific water and food dynamics were developed over the course of this thesis and applied alongside the more comprehensive LPJmL model. The parallel use of such models highlighted that high-resolution crop-hydrology models, and conceptual models at coarser spatial scales, are strongly complementary for obtaining a thorough understanding of future water-food interactions under deep uncertainty. Specifically, crop-hydrology models provide extensive information on potential future impacts for water and food security, but limited insight into how such impacts are influenced or caused by specific scenario drivers and associated assumptions about the future (Orth et al., 2015; Paola & Leeder, 2011). The parsimonious design of conceptual models instead allows the role of specific regional developments to be transparently explored, which proved crucial to establish larger trends and patterns at the basin level that allow for critical reflection on the detailed outcomes of crop-hydrology models. The adaptation pathways tool of Chapter 5 demonstrated similar methodological advantages. The spatial pathways essentially use two model outputs from the LPJmL model to provide actionable steps for various levels of integration between SDGs for water and food security, with a clear relation to the drivers and adaptation objectives. For general water-food assessments, developing increasingly accurate process-based modelling tools is therefore vital, but this thesis suggests there are also important benefits to be found in simpler assessments that fully disentangle the mechanics of specific drivers and uncertainties at more abstract levels and thus maintain sight of the big picture.

6.4. Final remarks and future outlook

This thesis provided a more detailed understanding than previous modelling studies of long-term drivers, trade-offs and adaptation strategies for SDGs related to water and food security in the Indus basin. The study outcomes first of all quantitatively demonstrated that socioeconomic and climatic changes will strongly intensify the pressure on water allocation and food production, especially on the densely populated Indus plains shared between India and Pakistan. This important agricultural region will face fast increasing competition for irrigation water by other water-use sectors, but must also produce more food to satisfy growing food demands in the basin. The inflow of crucial surface water from the upper Indus to the Indus plains will in addition become less reliable due to growing upstream demands and climate change. This means that without large-scale adaptive action, either unsustainable water use will increase here, or future food production targets cannot be met. These trade-offs make achieving the SDGs for both water and food security highly challenging in the future. Subsequent research steps showed that modifications to the food production system and water management practices can provide strong mutual benefits for water and food security objectives. Whether such technical changes can provide sufficient capacity to reconcile both SDGs on the long-term will however depend strongly on the type and direction of regional developments. Especially the rate of population growth and choices in relation to water allocation between upstream and downstream riparians were found to be important, but highly uncertain, factors for future adaptation challenges in the basin.

These findings indicate that the current interplay between water management and food production in the Indus basin is unsustainable in the long run. This means that in addition to technical changes to agriculture and water management, it is important to also account for alternative approaches and directions in adaptation planning. An important first step to integrate long-term water and food security objectives may be to redefine the objectives for agricultural development and food security. Instead of aiming for full regional self-sufficiency, water-intensive crops like sugarcane could for instance be imported, while export crops like cotton may be gradually replaced by staple crops. These far-reaching system changes have strong linkages with other development targets, such as economic development and energy security, and therefore increase interdependencies between riparians. Previous studies accordingly illustrated that transboundary cooperation in the Indus basin is essential for sustainable development (Kalair et al., 2019; Qamar et al., 2019; Rasul et al., 2021; Vinca et al., 2020), and this thesis comes to similar conclusions. This suggests that managing the sociopolitical dimensions of water and food security in the Indus basin may be as important to achieve the SDGs, if not more so, than exploring potential benefits of technical interventions. The modelling approach of this thesis used regionally detailed scenarios and stakeholder consultation workshops to incorporate numerous socioeconomic and sociopolitical elements. Nonetheless, the final conclusions based on these model outcomes mainly provide a top-down and technical understanding of adaptation challenges and strategies in the Indus basin.

An important future research line may therefore be found with transdisciplinary approaches that combine integrated modelling work, like the one used in this thesis, with socio-hydrology and political sciences. Recent studies show that the interplay between these disciplines can identify interesting modelling premises and scenario storylines that are targeted at regional political reality and can subsequently be made quantitative (Schütze et al., 2019). The inclusion of stakeholders from start to finish throughout this process may help bridge the gap between modelling outcomes and the information required by policy makers to address challenges for sustainable governance, the SDGs and climate change adaptation. In addition, a socio-hydrology perspective may be able to provide critical reflection and nuance to modelling outcomes for future developments that cannot be fully expressed in quantitative terms (Ocampo-Melgar et al., 2022). This may, for instance, help to understand value-based choices for priorities between future food self-sufficiency and sustainable water management in the Indus basin. These decisions on the balance between water and food security objectives proved to be an important dilemma in understanding how the corresponding SDGs may interact on the long-term, but were beyond the scope of this thesis to explore further. The use of socio-hydrological models that quantitatively simulate the dynamics of transboundary cooperation may also be an important next step (Khan et al., 2017; Lu et al., 2021). This study largely explored where upstream-downstream changes may lead to tension, so alternative approaches that look for transboundary benefits are crucial to highlight potential opportunities for cooperation.

In a similar manner, two-way interactions between modelling outcomes and the intended audience may help to interpret more local implications for SDGs from regional modelling studies. The modelling approach used in this thesis has a high spatial resolution, but the assumptions, premise and interpretation are all essentially for the regional level. Model outcomes were used to inform and guide reflection workshops with policy makers, but the ensuing discussions subsequently largely revolved around regional implications. Innovative tools that allow stakeholders to instead interact directly with simulated data itself, and flexibly add locally relevant parameters, may help draw more specific and policy relevant insight during such workshops (Goosen et al., 2014). For instance, the Climate Impact Atlas uses numerous layers of future climatic projections, but due to an intuitive interface allows such data to be fluently accessed at street level for myriad relevant indicators of potential climate change effects (Goosen et al., 2009). Improving local insights and stakeholder engagement for adaptation planning may thus rest more with translating the vast amount of existing data into more user friendly formats, than with using novel scientific approaches to create more, or even higher resolution, data products itself. This suggest it is also important for modelling research to engage with professionals outside of the sciences, such as storywriters, designers, visual artists and application developers, that may help to take scientific data out of its inaccessible formats and towards products that resonate more with the general public (Grainger et al., 2016; Schneider, 2012).

In the end, this thesis clearly demonstrates that the setting of water and food security in the Indus basin is so complex, that there is still much future work to be done for all sorts of scientific fields and professional services to better understand how the SDGs can be achieved. This thesis made small, but significant, advances towards better understanding a subset of this major challenge by quantitively integrating developments for future water and food security. As a general recommendation for future studies in the Indus basins, this thesis concludes that further integration and more cooperation, whether between sectors, scientific disciplines, riparian states or between science and policy, is key towards achieving the SDGs. This type of collaboration can help to ensure that adaptation strategies are both technically feasible and societally acceptable, thus providing a sustainable basis for a water and food secure basin far beyond 2030.

Appendix

Appendix A

Table A1: Overview of multi-sectoral matching of SSPs to regional narratives.

Indicator	States	SSP	HKH
Climate Change	High / 6.0 - 8.5	2, 3 & 5	Down. & BUA
	Moderate / 4.5 - 6.0	1 & 4	Prosp.
	Low / 2.6 - 4.5	-	-
Environmental Protection	High	1	Prosp.
	Moderate	2 & 4	BUA
	Low	3 & 5	Down.
Global Connection & Trade	Restricted	3	Down.
	Moderate	2 & 4	BUA
	Global & Free	1 & 5	Prosp.
Institutional Strength Developing Regions	Weak	3	Down.
	Moderate	2, 4 & 5	BUA
	Strong	1	Prosp.
Population Growth	High	3 & 4	Down.
	Moderate	2	BUA
	Low	1 & 5	Prosp.
Urbanisation Rate	High	1, 4 & 5	Down. & BUA & Prosp.
	Moderate	2	-
	Low	3	-
Urbanisation Form	Poorly managed	3	Down.
	Moderate	2 & 4	BUA
	Well managed	1 & 5	Prosp.
Poverty	High	3	Down.
	Moderate	2 & 4	BUA
	Low	1 & 5	Prosp.
Inequality	High	3, 4	Down.
	Moderate reduction	2	BUA
	Reduced	1, 5	Prosp.
Vulnerability to Climate Change	High	3 & 4	Down.
	Moderate	2 & 5	BUA
	Low	1	Prosp.
Economic Growth	High	5	Prosp.
	Moderate	1 & 2	BUA
	Low	3 & 4	Down.
Technological Development	Slow	3	Down.
	Moderate	2 & 4	BUA
	Rapid	1 & 5	Prosp.

Table A2: Comparison basin factor established via HYDE dataset versus census data.

Year	Difference population growth rate India basin share vs national level - HYDE	Difference population growth rate India Basin share vs national level - Census
1991	1.382.594	1.140.856
1992	1.382.594	1.140.856
1993	1.382.594	1.140.856
1994	1.382.594	1.140.856
1995	1.382.594	1.140.856
1996	1.382.594	1.140.856
1997	1.382.594	1.140.856
1998	1.382.594	1.140.856
1999	1.382.594	1.140.856
2000	1.382.594	1.140.856
2001	1.017.015	1.085.185
2002	1.017.199	1.085.185
2003	1.017.382	1.085.185
2004	1.017.563	1.085.185
2005	1.017.743	1.085.185
2006	1.017.923	1.085.185
2007	10.181	1.085.185
2008	1.018.275	1.085.185
2009	1.018.451	1.085.185
2010	1.018.622	1.085.185
2011	1.021.116	No Data
2012	1.021.251	No Data
2013	110.044	No Data
2014	1.002.645	No Data
2015	1.002.612	No Data
2016	1.002.579	No Data
Basin Factor	**1.159.802**	**1.113.021**

Table A3: Explanatory variable layers and their weighting per scenario. Additionally, for every layer the data source, data analysis process and key assumptions are clarified.

Layer	Type	Weighting			Data Source
		Pros.	*BuA.*	*Down.*	
Current Urban Area	Boundary condition	NA	NA	NA	Initial current urban area was assessed on a per country basis with the gridded population count and -density estimates for 2015 of the HYDE 3.2 dataset (Klein Goldewijk et al., 2011). Cells were identified as urban by ordering initial HYDE cells by population density and iteratively aggregating their population count until the sum equalled the country urban population total. For further timesteps current urban area was based on the results of the previous timesteps.
Border zones	Boundary condition	0	0.25	0.5	Grid cells that form part of the border zones were selected by identifying all cells that fall within 40 kilometres of national borders (Bala & Krishan, 1982), using the Natural Earth 10 meter country shapefile dataset(Kelso & Patterson, 2010). The natural logarithm of these grid cells was taken and the result was normalized. The resulting index was multiplied by the scenario border factor to create a gridded, gradual border factor layer.
Terrain suitability	Explanatory variable & boundary condition	2	2	2	Suitability of terrain was assessed using a high resolution DEM and -slope map at 15 arcsec, and a 30-metre resolution 1984-2015 mean surface water presence dataset (Pekel et al., 2016). All 15 arcsec grid cells that were above 4000 meters or had a slope greater than 10% were considered unsuitable. A terrain suitability index was created at 5 arcmin resolution by determining the fraction of suitable 15 arcsec cells and subtracting the aggregated mean surface water presence fraction.
Distance to urban area	Explanatory variable	95	95	43	Distance to urban area was assessed per country by calculating the distance in kilometres of all non-urban grid cells to the closest grid cells defined as urban in the 'current urban area' layer. To create a suitability index, the natural logarithm of distance in kilometres was taken and the resulting values were normalized.
Distance to major city	Explanatory variable	8	15	30	Distance to major cities was assessed per country by calculating the distance in kilometres of all grid-cells to the closest city of over 1 million in population, using the spatial IBM CCIP cities database (IMB, 2019). To create a suitability index, the natural logarithm of distance in kilometres was taken and the resulting values were normalized.
Distance to main road	Explanatory variable	5	5	5	Distance to the main road network was assessed per country by calculating the distance in kilometres of all grid cells to the closest main road, using shapefiles of roads defined as 'motorway' or 'trunk' in the OpenStreetMap highway database (OSM, 2015). To create a suitability index, the natural logarithm of distance in kilometres was taken and the resulting values were normalized.
Highland-lowland region	Explanatory variable	0	1	2	Lowland regions were assessed by taking the mean elevation of the second level administrative units within the Indus basin using a 15 arcsec DEM and 10 meter administrative shapefiles from the Natural Earth dataset (Kelso & Patterson, 2010). All administrative units with a mean elevation below 1000 metres were considered lowland regions. Lowland regions in Pakistan were defined as: Punjab, Sindh & Federal Capital. In India: Punjab, Rajasthan, Chandigarh, Haryana & Gujarat. In the Afghani and Chinese Indus basin shares no lowland provinces were identified. A binary index was created by indicating provinces as either highland or lowland.

Appendix B

Future industrial and domestic water demand

Formulas to determine industrial (1) and municipal (2) water consumption from Bijl et al. (2016) whereby C stands for the consumption (m3/yr) for the industrial (I) and municipal (M) sector for year t and region r. The models first determine the structural withdrawals for a region in a year, for which V is the economic driving force of total industry value added (US$/yr), P is the population (yr), G is the is the level of economic development (expressed in $US GDP per capita/yr). These are then multiplied by a static region factor (R) that accounts for cultural factors, a static consumption fraction (F) and an annual efficiency factor (E). The industrial model moreover has two parameters, α and b, that were calibrated at 3.57 and −0.564 respectively. The municipal model contains two parameters, m, and s, that were calibrated at 8.575 and 0.6985 respectively. Additionally a midpoint (c) was defined at 143.5 (m3/cap/yr) by Bijl et al. (2016). The economic and population data to run these models were sourced from Smolenaars et al. (2021) and are described in the methodology. The region factors, consumption fraction and efficiency factors were sourced from Bijl et al. (2016).

$$C_r^I = V_r(t) * \alpha * G_r(t)^b * R_r^I * F_r^I * E_r^i(t) \quad (1)$$

$$C_r^M = P_r(t) * \frac{c}{1+e^{\left(\frac{m-\ln(G_r(t))}{s}\right)}} * R_r^M * F_r^M * E_r^M(t) \quad (2)$$

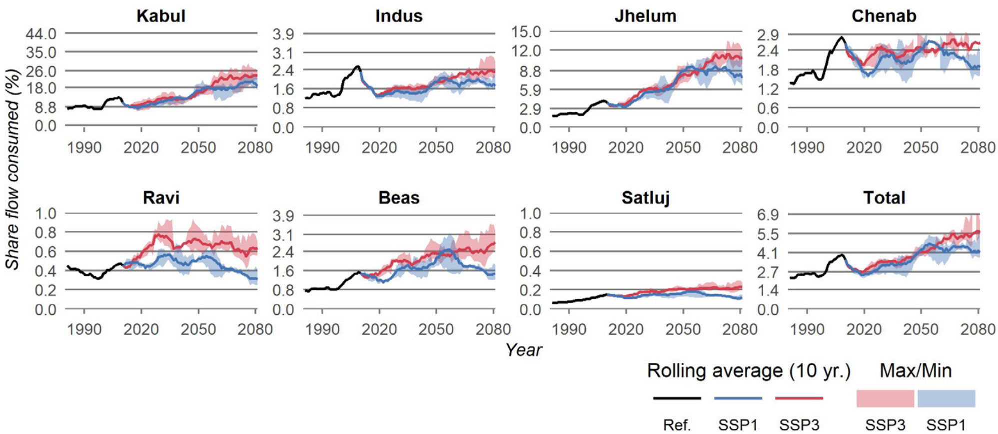


Figure B1: Share of annual discharge consumed per sub-basin and for the total upper Indus basin.

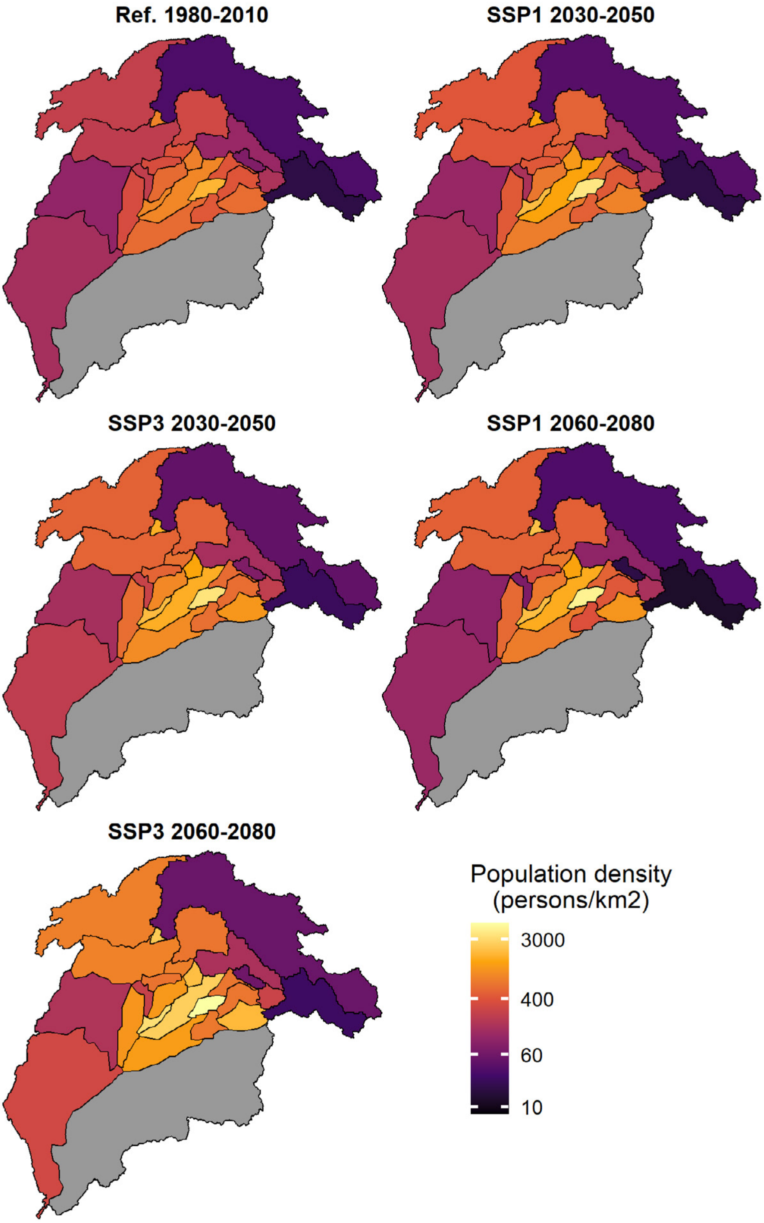


Figure B2: Population density of each upper and lower Indus sub-basin through time and for both scenarios, as used in this study. The population projections were sourced from Smolenaars et al (2022). They were developed by spatially downscaling the national population projections of the global SSP framework using regionalized population model that considers for urbanization, internal highland-to-lowland migration and proximity to infrastructure. These drivers were weighted relative to the scenario context sourced from both the global SSPs and pre-existing qualitative regional development storylines developed by Roy et al. (2019).

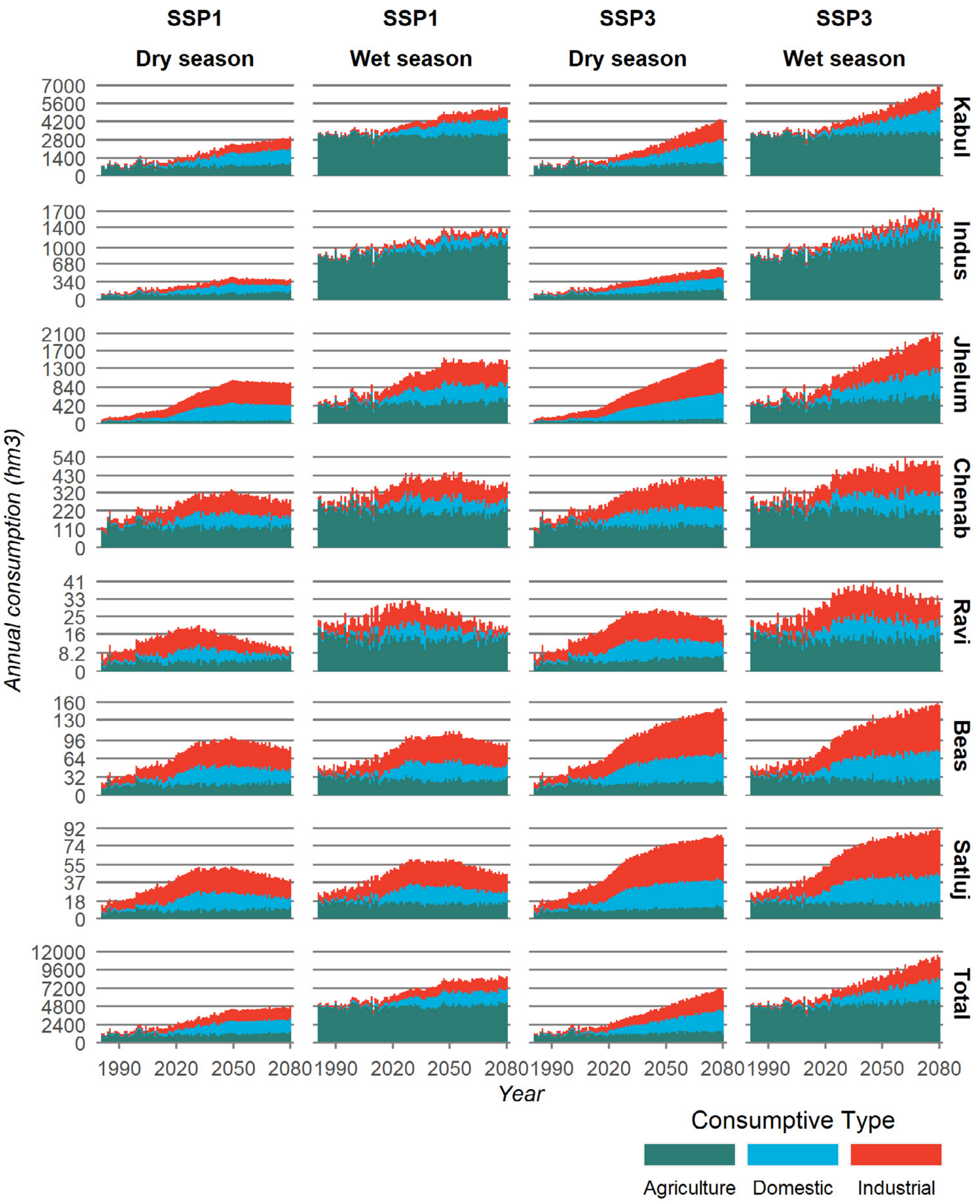


Figure B3: Domestic, industrial and agricultural water development per season and scenario.

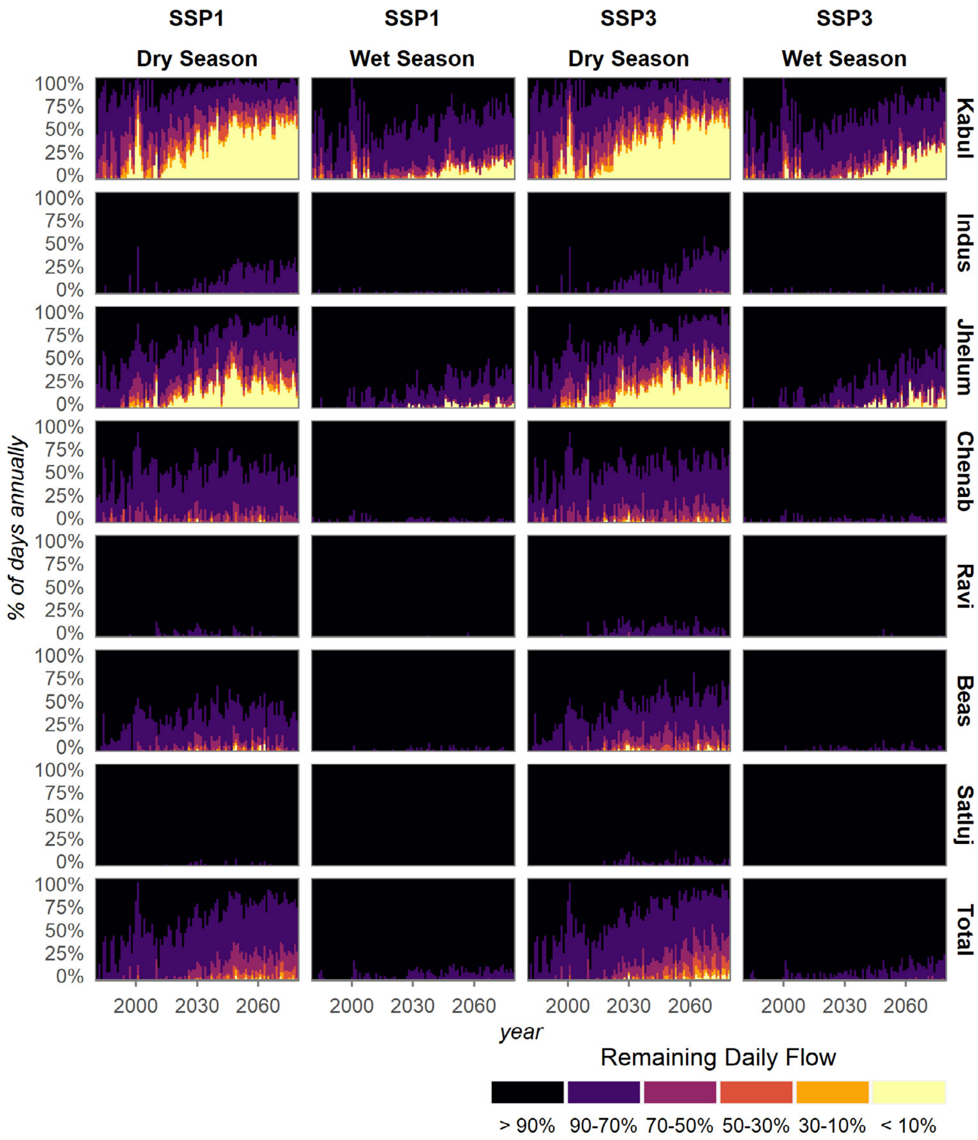


Figure B4: Development of the daily remaining flow per season and per scenario.

Appendix C

Translating agricultural development narratives to land-use projections

To translate the agricultural development strategies into tangible and quantitative land-use projections, we used a three-step approach:

1. First, for each crop group, we assessed the total net sown area per cropping season (Kharif/wet season, and Rabi/dry season) within the Indus basin over the historical period 1950-2015, using sub-national level agricultural statistics (see Appendix C). For states or provinces that are not fully part of the Indus basin (such as Rajasthan), we determined the ratio of cropped area that lies within the basin boundaries in the year 2005 using the gridded MIRCA-2000 dataset (Portmann et al., 2010). These ratios were assumed to be constant over the entire historical period and applied to the historical net sown areas of these administrative entities as per the sub-national statistics. In case of missing sub-national data, national agricultural statistics were used to interpolate gaps. Specifically, we corrected the national net sown area of the affected crop group by the fraction that the relevant sub-national entity represented in the national total, in the closest years with available data.
2. Next, the historical change in net sown area for staple food crops (wheat, rice, maize) in both riparian states was correlated to the historical population change within the basin share of both riparian states. To obtain population figures, we used sub-national census data and the spatially explicit HYDE population dataset(Klein Goldewijk et al., 2011). The crop-and-country-specific coupling between net-sown area and population was then extrapolated to 2080 using the population projections for the Indus basin of both SSP-RCP scenarios. Similarly, the present rate at which sugarcane replaces cotton was determined and extrapolated over the projected period. The net sown area of oilseeds and pulses, and the other crops group were left to 2015 conditions. This provided a set of baseline projections of net-sown area of the crop groups, for each SSP-RCP scenario and for both seasons. The proposed changes in crop mix, land-use intensity and irrigation intensity as per the three agricultural development narratives (see Table 1) were then applied to these baseline projections. We used state-level land-use statistics to determine the boundary constraints in terms of available fallow land and cropping intensity (see Appendix A).
3. We spatialized the land-use projections for the agricultural development strategies using a similar approach to Wijngaard et al. (2018) and Smolenaars et al. (2022). First, the spatially explicit MIRCA-2000 dataset (Portmann et al., 2010) was cropped for the Indus basin and corrected, for both cropping seasons and countries, to align exactly with the net sown area statistics of the year 2005. We then applied at annual timesteps towards 2080 the projected change rates of each crop group in each country to the corrected 2005 crop map. The change rate was applied proportionally to the net sown area of a crop in each cell, up until the cell reached full potential cropping intensity, in which case any surplus area was divided proportionally over all other cells with remaining space. To account for the effect of agricultural-urban competition for land (Farah et al., 2019), urban areas were made unavailable when determining the full potential cropping intensity of a cell, using urbanization data by Smolenaars et al. (2021). Our approach thereby implicitly assumed that the cultivation of all crops remains in the same location as at present. This guarantees present biophysical suitability in terms of terrain and climate, and ensures access to the irrigation network. We similarly applied the historical annual change rates to the 2005 base map up until reaching 1950.

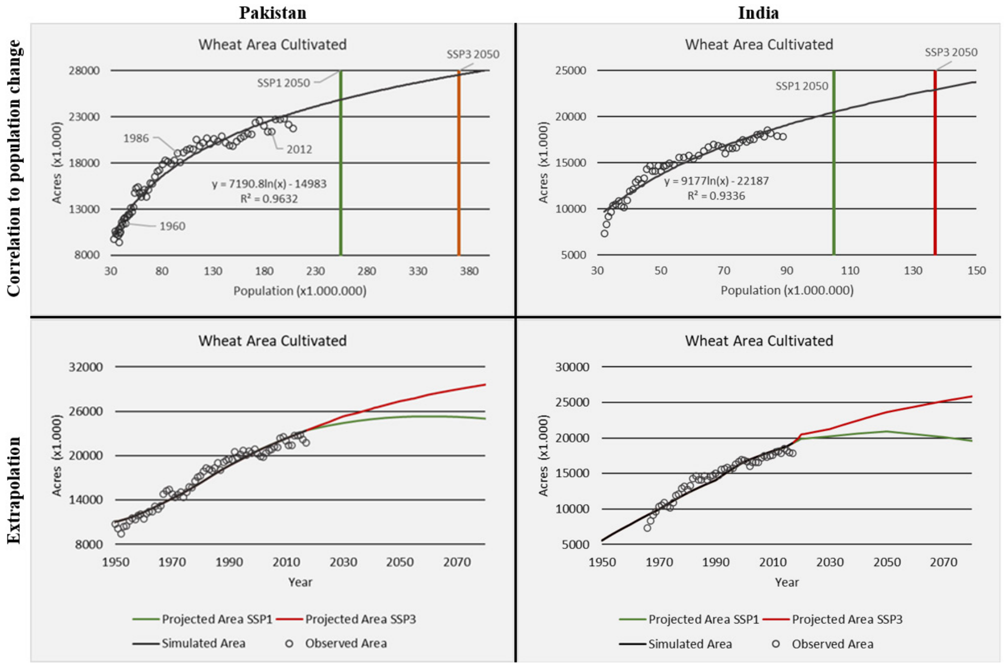


Figure C1: Baseline trend extrapolation for wheat area in relation to population change.

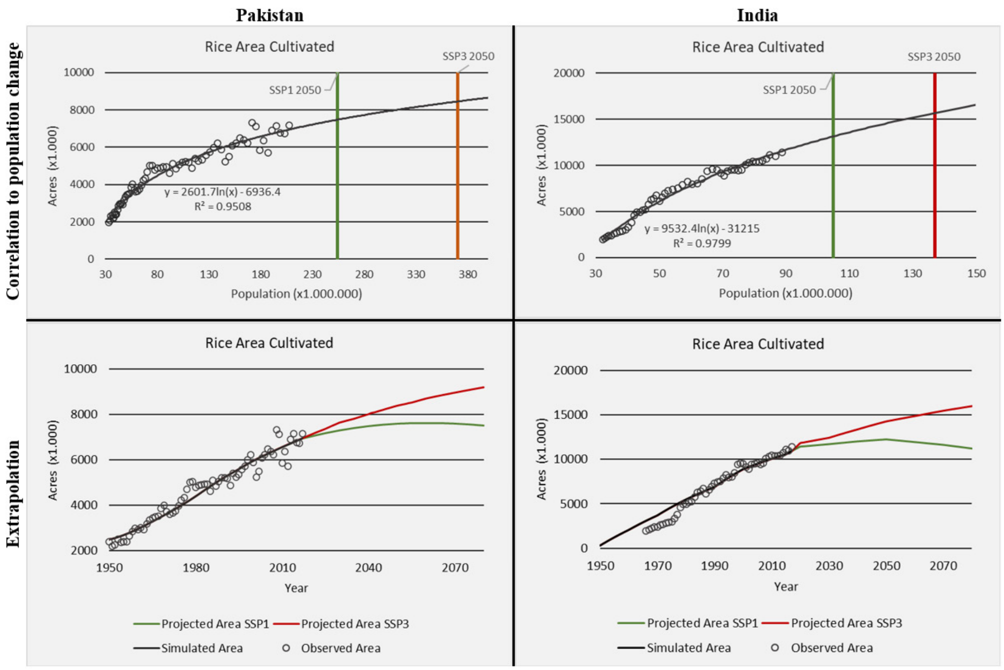


Figure C2: Baseline trend extrapolation for rice area in relation to population change.

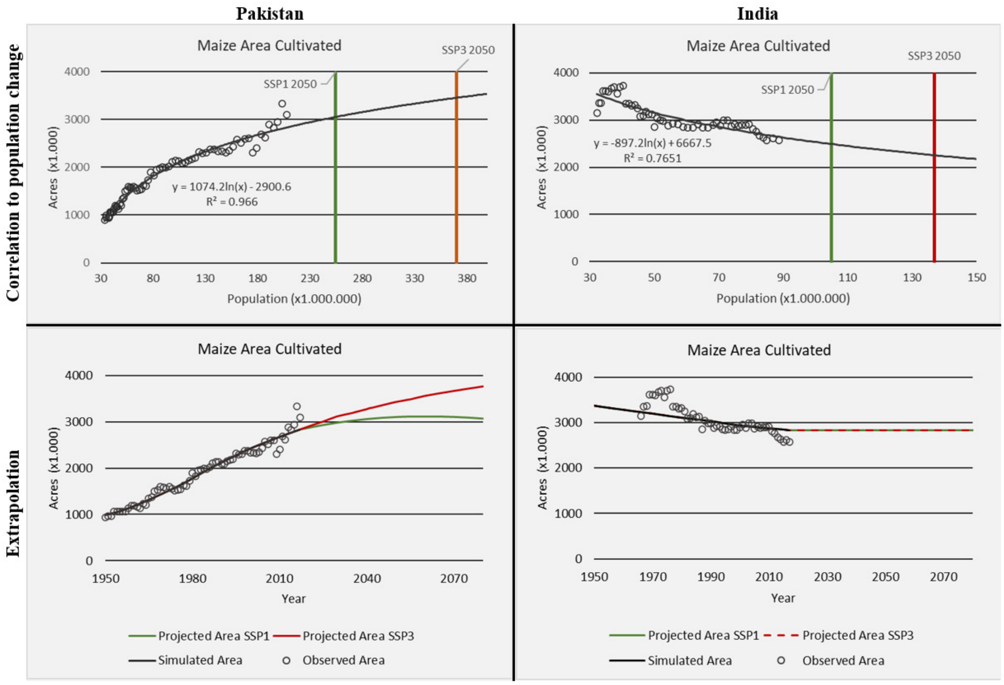


Figure C3: Baseline trend extrapolation for maize area in relation to population change.

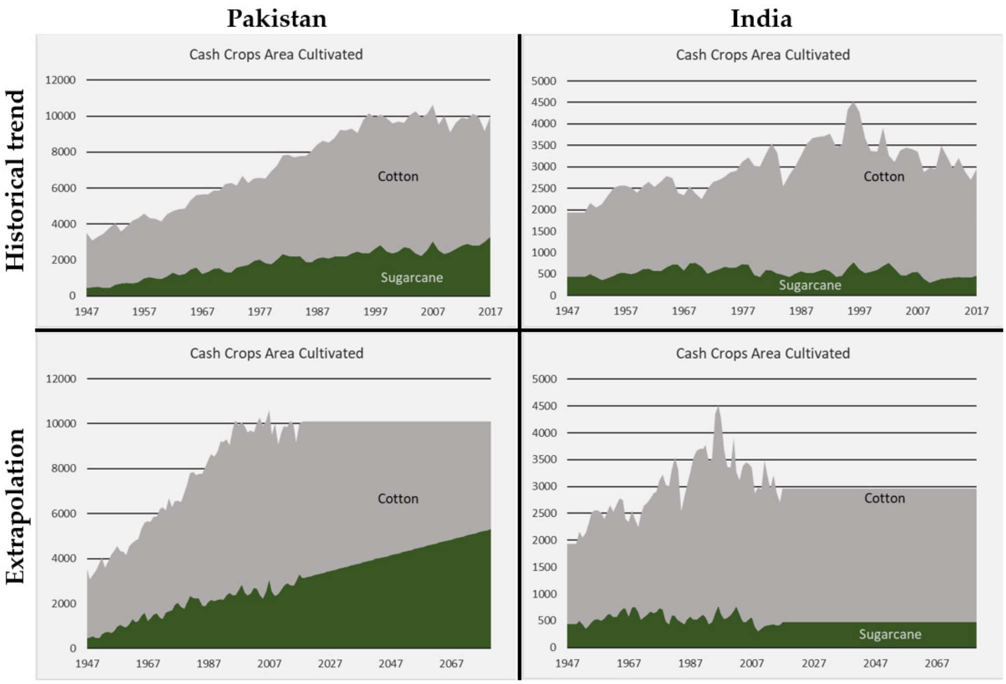


Figure C4: Baseline trend extrapolation for cash crop area.

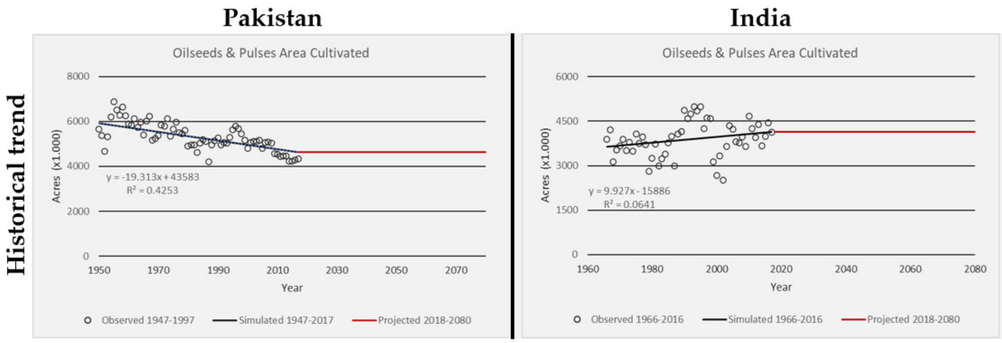


Figure C2: Historical trend analysis oilseeds & pulses.

Table C1: Factsheet stakeholder workshop land-use futures

Title:	National consultation workshop; exploring future land-use innovations for water and food security in the Indus basin.
Date:	16-05-2022 from 10:00 until 16:00.
Place:	National Agricultural Research Center (NARC) Islamabad.
Amount of participants:	Between 22 and 32 at various stages of the workshop.
Type of participants:	The consultative workshop was attended by: Diverse representatives of the international scientific community, including senior scientists from the Pakistan Agricultural Research Council (PARC), the Pakistan Council of Research on Water Resources (PCRWR), the country head of the International Centre for Integrated Mountain Development (ICIMOD), and several early carrier researchers from various local universities. NARC crop experts on wheat, rice, sugarcane, cotton, fodders and grassland, oilseed crops, pulses, vegetables, fruit orchards, and other horticultural crops. Government officials from the Federal Ministry of Food Security and Research of Pakistan.
Objective:	To gather local insights from land and water management experts, crop experts, and other relevant stakeholders and policymakers that can support and validate the development of plausible and diverse agricultural system change scenarios for the Indus river basin.
Approach:	The consultative workshop started by providing an overview of different modelling tools for geospatial analysis used by the authors of this study to quantify the impacts of agricultural system changes on the water and food security of the Indus basin. Subsequently, an overview of three future agricultural development strategies was provided. These strategies were developed earlier using the literature review and local knowledge by the project's local partners. Next, the floor was opened for multiple rounds of consultative process and participants discussion to validate or edit the developed agricultural development strategies. Lastly, the participants were briefed on several Climate-Smart Agriculture innovations that are currently being piloted, and their importance and limitations were discussed.
Key results:	The primary outcome of the workshop is that most local experts approved and validated the developed land-use scenarios. Participants showed great interest in learning the upscaling assessment methods, as this is one of the missing links in the current literature for Pakistan. Almost all of the experts agreed with replacing the high water delta crops with low water delta in a Water Limited strategy. However, it is essential to mention that senior researchers also stressed the current and future economic importance of certain high water delta crops, as they are one of the significant sources of foreign exchange, and thereby somewhat mitigate the trade deficit of the riparian states of the Indus basin. Subsequently, for the Food Priority, the participants agreed with the continued expansion of these crop categories to boost exports and limit imports. In addition, it was argued that the narratives at the core of the current strategies focus largely on water and food in biophysical terms. The economic impact of changes is however clearly of importance as well, and it was deemed important by participants to reflect more in the study on this aspect of agricultural system change.

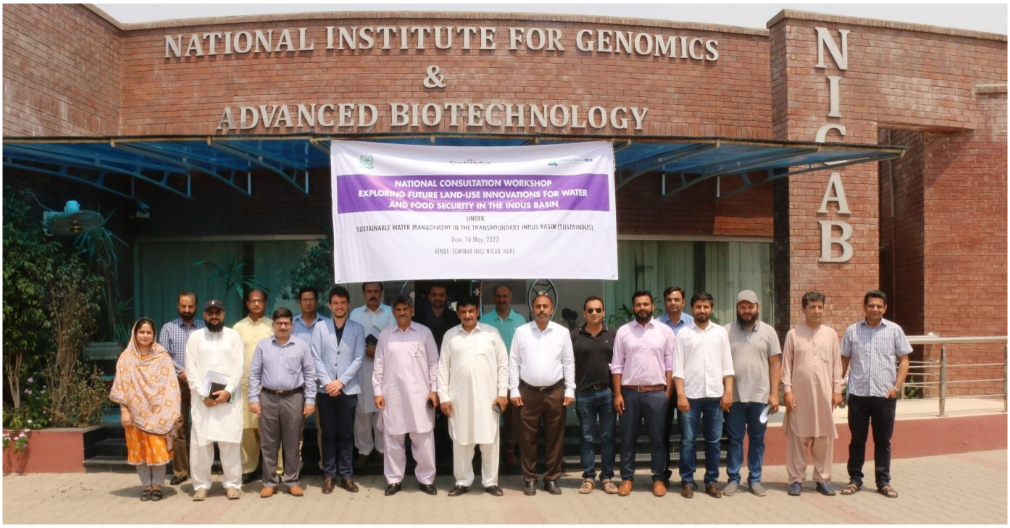


Figure C6: Participant group photo at the start of the stakeholder workshop

Table C2: Overview of policy documents, regional statistics and reports used to develop agricultural system narratives and translate these into strategies.

Content Description	Country	Reference
Survey and perspective report on future of the agricultural economy.	Pakistan	Finance Division Government of Pakistan (2021). Pakistan Economic Survey: Agriculture. I. Ahmad.
Pakistan agricultural yearbook of facts.	Pakistan	Ministry of National Food Security and Research (2016). Agricultural Yearbook. J. Humayun.
Pakistan agricultural and land-use statistics.	Pakistan	Ministry of National Food Security and Research (2018). Agricultural Statistics of Pakistan 2017-18. M. A. Talpur.
Pakistan land utilization statistics.	Pakistan	Pakistan Bureau of Statistics (2021). Land Utilization Statistics. https://www.pbs.gov.pk/sites/default/files/tables/agriculture_statistics/table_3_land_utilization_statistics.pdf
Agricultural profile of the Punjab province.	Pakistan	Punjab Agricultural Department (2017). Punjab Agriculture Profile. Agriculture Department.
Punjab long term agricultural strategy report.	Pakistan	The Urban Unit Technical Paper 5 Agricultural Development. Punjab Spatial Strategy 2047. W. Khan, Planning and Development Department under Government of the Punjab.
National food security strategy.	Pakistan	Ministry of National Food Security and Research (2014). National Food Security Policy. S. H. K. Bosan, Government of Pakistan.
National food system strategy.	Pakistan	Ministry of National Food Security and Research (2021). National Pathways for Food Systems Transformation in Pakistan. T. Khurshid, Government of Pakistan.
Water for agriculture analysis and strategy.	Pakistan	Qureshi, R. and M. Ashraf (2019). "Water security issues of agriculture in Pakistan." PAS Islamabad Pak 1: 41.
National Water Strategy.	Pakistan	Ministry of Water Resources (2018). National Water Policy. S. Aziz, Government of Pakistan.
Agricultural profile of the Punjab state.	India	Grover, D., et al. (2017). State Agricultural Profile -Punjab.
Punjab agricultural perspectives report.	India	Indian Council for Research on International Economic Relations (2017). Getting Punjab Agriculture Back on High Growth Path: Sources, Drivers and Policy Lessons. A. R. Gulati, Ranjana; Hussain, Siraj.
Punjab farmer guide & land-use statistics.	India	Department of Agriculture & Cooperation Mechanisation & Technology Division. (2022). Punjab Farmers' Guide, Ministry of Agriculture, Government of India. https://farmech.dac.gov.in/FarmerGuide/PB/index1.html
Haryana farmer guide & land-use statistics.	India	Department of Agriculture & Cooperation Mechanisation & Technology Division (2022). Haryana State Farmer Guide, Ministry of Agriculture, Government of India. https://farmech.dac.gov.in/FarmerGuide/HR/index1.html
Rajasthan farmer guide & land-use statistics.	India	Department of Agriculture & Cooperation Mechanisation & Technology Division (2022). Agricultural Mechanization Guide for Rajahstan, Ministry of Agriculture, Government of India. https://farmech.dac.gov.in/FarmerGuide/RJ/index1.html
Jammu and Kashmir farmer guide & land-use statistics.	India	Department of Agriculture & Cooperation Mechanisation & Technology Division (2022). Jammu & Kashmir Farmers' Guide, Ministry of Agriculture, Government of India. https://farmech.dac.gov.in/FarmerGuide/JK/index1.html
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India state-wise agricultural and land-use statistics.	India	Directorate of Economics and Statistics (2022). State Wise Area Production & Yield Statistics (1966 to 2016), Department of Agriculture and Cooperation, Ministry of Agriculture and Farmers Welfare, Government of India. https://eands.dacnet.nic.in/APY_96_To_07.htm
Water for agriculture analysis and strategy.	India	Dhawan, V. (2017). Water and Agriculture in India, Background paper for the South Asia expert panel during the Global Forum for Food and Agriculture (GFFA) 2017, German Asia-Pacific Business Association.
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National sustainable agriculture plan.	India	Expert Scientific Committee (2019). Policies and Action Plan for a Secure and Sustainable Agriculture. R. S. Paroda, Government of India.
National agricultural economy plan.	India	Chand, R. (2019). Presidential Address, Transforming Agriculture for Challenges of 21st Century. Indian Economic Journal, December. 102 Annual Conference Indian Economic Association Niti Aayog Government of India.

Figure C7: Comparison of simulated to observed total production for five major crops.

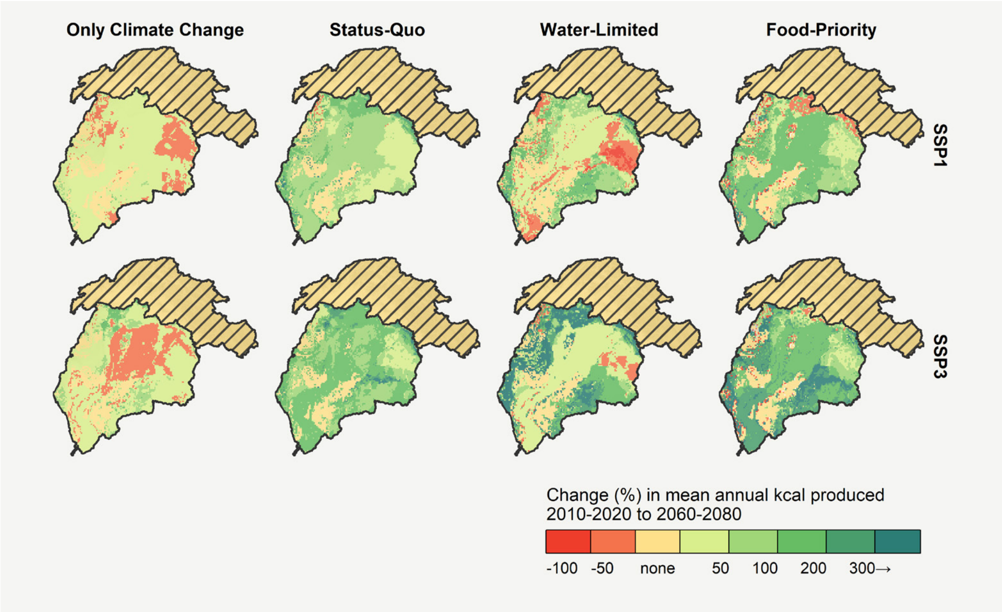

Figure C8: Change in total kcal produced at the grid cell level.

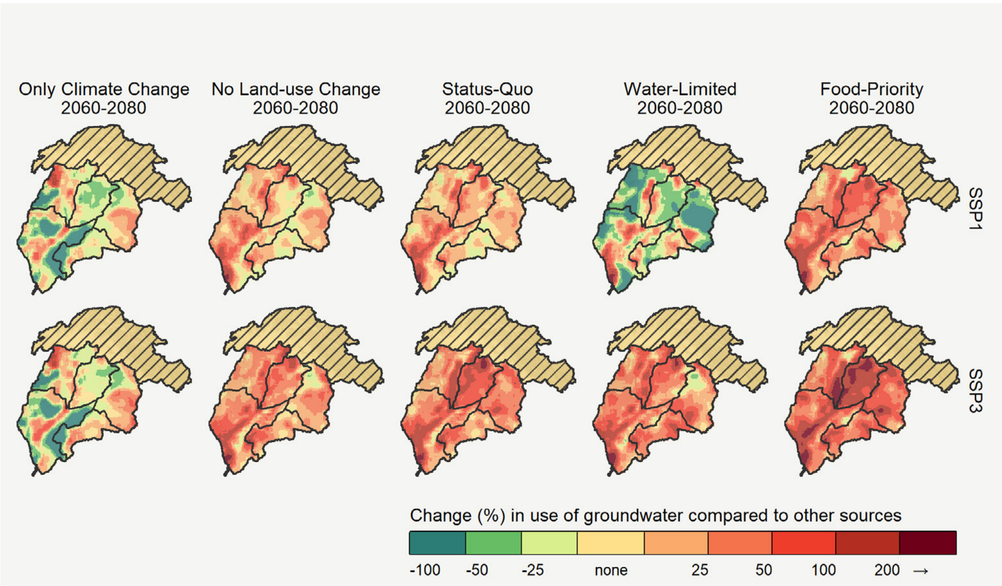

Figure C9: Change in total kcal produced at the grid cell level.

Appendix D

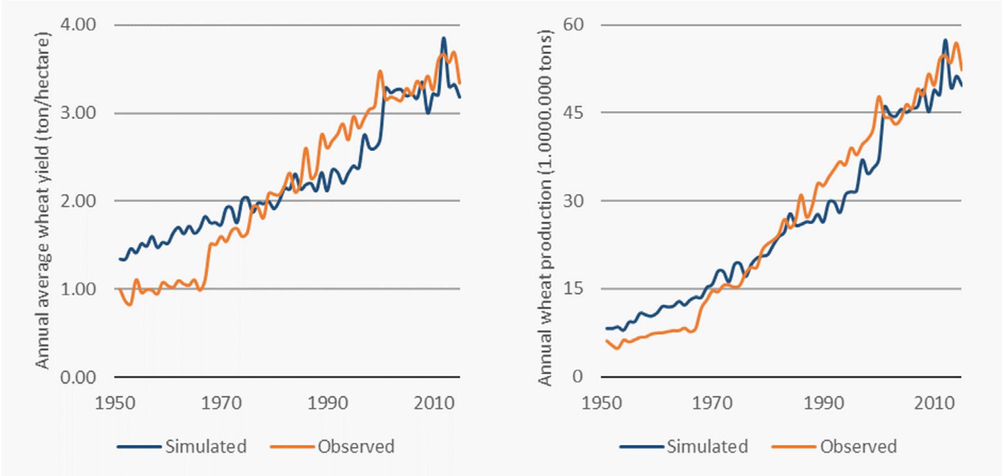

Figure D1: Comparison of simulated average wheat yield (left) and total production (right) to observed statistics.

Table D1: Overview of water footprint values for irrigated wheat production in the Indus basin found in scientific literature.

#	Water footprint		Reference
	m3/ ton	*Location*	
1.	1500 to 3000	Punjab, Pakistan.	Khan, T., Nouri, H., Booij, M. J., Hoekstra, A. Y., Khan, H., & Ullah, I. (2021). Water Footprint, Blue Water Scarcity, and Economic Water Productivity of Irrigated Crops in Peshawar Basin, Pakistan. Water, 13(9), 1249.
2.	1478	Pakistan (full country).	Mekonnen, M. M., & Hoekstra, A. Y. (2010). A global and high-resolution assessment of the green, blue and grey water footprint of wheat. Hydrology and earth system sciences, 14(7), 1259-1276.
3.	1173	India (full country).	
4.	1341	Sindh, Pakistan (based on mm with fixed yield m2).	Solangi, G. S., Shah, S. A., Alharbi, R. S., Panhwar, S., Keerio, H. A., Kim, T. W., ... & Bughio, A. D. (2022). Investigation of Irrigation Water Requirements for Major Crops Using CROPWAT Model Based on Climate Data. Water, 14(16), 2578.
5.	1544	Haryana, India (based on mm with fixed yield m2).	Pakhale, G., Gupta, P., & Nale, J. (2010). Crop and irrigation water requirement estimation by remote sensing and GIS: A case study of Karnal district, Haryana, India. International Journal of Engineering and Technology, 2(4), 207-211.
6.	910 to 1050	Sindh, Pakistan (only net irrigation requirements).	Memon, S. A., Sheikh, I. A., Talpur, M. A., & Mangrio, M. A. (2021). Impact of deficit irrigation strategies on winter wheat in semi-arid climate of sindh. Agricultural Water Management, 243, 106389.
7.	1065 to 1405	Punjab, Pakistan (assuming full irrigation application).	Jabeen, M., Ahmed, S. R., & Ahmed, M. (2022). Enhancing water use efficiency and grain yield of wheat by optimizing irrigation supply in arid and semi-arid regions of Pakistan. Saudi Journal of Biological Sciences, 29(2), 878-885.
8.	904 and 1955	Punjab, India (based on mm with fixed yield m2).	Satpute, S., Singh, M. C., & Garg, S. (2021). Assessment of irrigation water requirements for different crops in central Punjab, India. Journal of Agrometeorology, 23(4), 481-484.

Table D2: Overview of water savings (WS) and yield gains (YS) for irrigated wheat production due to laser land levelling per soil type found in scientific literature.

#	**Water savings and yield gains per soil type**						**Reference**
	Sandy-loam		*Loam*		*Clay-loam*		
	WS	*YG*	*WS*	*YG*	*WS*	*YG*	
1.	50%	21%	33%	14%	15%	18%	Jamil, M. K., Smolenaars, W. J., Ahmad, B., & Biemans, H. (2022). Spatial quantification of the potential of laser land leveling to reduce water demand for irrigated wheat production in the Indus river basin. Crop and Pasture Sciences [submitted].
2.	30%	9%	-	-	30%	7%	Aryal, J. P., Mehrotra, M. B., Jat, M. L., & Sidhu, H. S. (2015). Impacts of laser land leveling in rice–wheat systems of the north–western indo-gangetic plains of India. Food Security, 7(3), 725-738.
3.	-	-	21%	6%	-	-	Pardeep, K., Vineet, K., & Sanjeev, K. (2014). Evaluation of the laser leveled land leveling technology on crop yield and water use productivity in Western Uttar Pradesh. African Journal of Agricultural Research, 9(4), 473-478.
4.	-	-	-	-	21%	18%	Das, A., Lad, M. D., & Chalodia, A. L. (2018). Effect of laser land leveling on nutrient uptake and yield of wheat, water saving and water productivity. Journal of Pharmacognosy and Phytochemistry, 7(2), 73-78.
5.	-	-	-	9%	-	-	Aryal, J. P., Khatri-Chhetri, A., Sapkota, T. B., Rahut, D. B., & Erenstein, O. (2020, August). Adoption and economic impacts of laser land leveling in the irrigated rice-wheat system in Haryana, India using endogenous switching regression. In Natural Resources Forum (Vol. 44, No. 3, pp. 255-273). Oxford, UK: Blackwell Publishing Ltd.
6.	20%	8%	-	-	-	-	Jat, M. L., Gathala, M. K., Ladha, J. K., Saharawat, Y. S., Jat, A. S., Kumar, V., ... & Gupta, R. (2009). Evaluation of precision land leveling and double zero-till systems in the rice–wheat rotation: Water use, productivity, profitability and soil physical properties. Soil and Tillage Research, 105(1), 112-121.
7.	-	-	31%	20%	-	-	Latif, A., Shakir, A. S., & Rashid, M. U. (2013). Appraisal of economic impact of zero tillage, laser land levelling and bed-furrow interventions in Punjab, Pakistan. Pakistan Journal of Engineering and Applied Sciences.
8.	49%	7%	-	-	-	-	Jat, M. L., Sharma, S. K., Gupta, R. K., Sirohi, K., & Chandana, P. (2005). Laser land leveling: the precursor technology for resource conservation in irrigated eco-system of India. Conservation Agriculture-Status and Prospects, CASA, New Delhi, 145-154.
9.	41%	16%	-	-	-	-	Ambast, S. K. (2007). Land Levelling: An On Farm Water Management Strategy for Improving Crop Productivity in Saline Environment. Agricultural Land Drainage, 70.
10.	-	-	-	23%	-	-	Chen, J., Zhao, C., Jones, G., Yang, H., Li, Z., Yang, G., ... & Wu, Y. (2022). Effect and economic benefit of precision seeding and laser land leveling for winter wheat in the middle of China. Artificial Intelligence in Agriculture, 6, 1-9.
11.	40%	21%	-	-	-	-	Eid, A. R., Mohamed, M. H., Pipars, S. K., & Bakry, B. A. (2014). Impact of laser land leveling on water productivity of wheat under deficit irrigation condations. Current research in agricultural sciences, 1(2), 53-64.
12.	-	-	-	-	-	17%	Antar, A. S., Khafagi, H. A., Nasr El-Din, I. E., & El-Saiad, I. A. (2012). EFFECT OF TILE DRAINAGE AND LASER LAND LEVELING ON SOME SOIL PROPERTIES AND PRODUCTION OF SUGAR BEET AND WHEAT CROPS. Journal of Soil Sciences and Agricultural Engineering, 3(1), 1-15.
13.	47%	15%	-	-	-	-	Shahani, W. A., Kaiwen, F., & Memon, A. (2016). Impact of laser leveling technology on water use efficiency and crop productivity in the cotton-wheat cropping system in Sindh. International Journal of Research Granthaalayah, 4(2), 220-231.
14.	-	-	-	-	13%	30%	Hoque, M. A., & Hannan, M. A. (2014). Performance evaluation of laser guided leveler. International Journal of Agricultural Research, Innovation and Technology (IJARIT), 4(2355-2020-1576), 82-86.

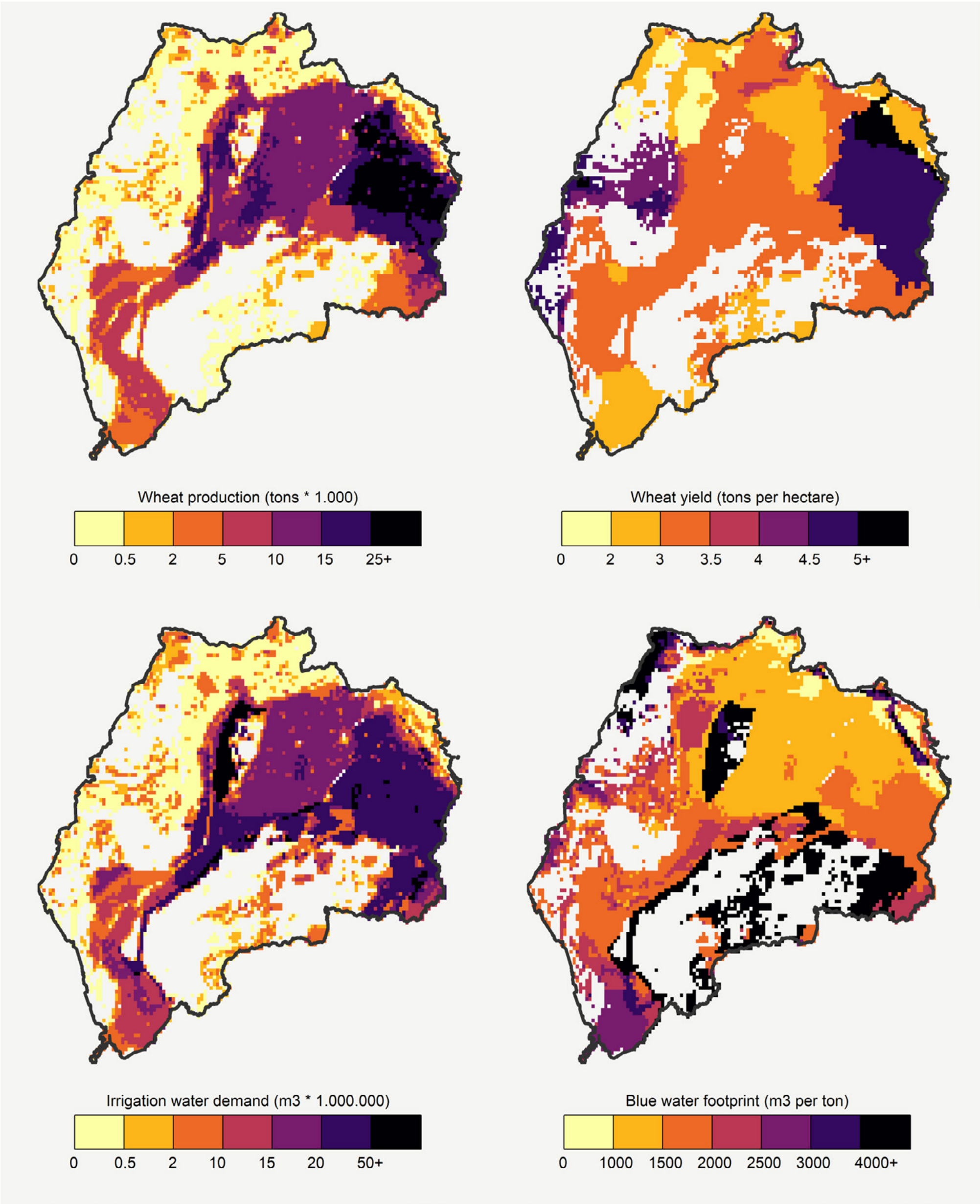

Figure C9: Simulated wheat production (top left), yield per hectare (top right), irrigation water demand (bottom left) and blue water footprint (bottom right) for 2015 under reference conditions.

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Summary

The Indus basin is home to over 270 million people and is shared between Pakistan, India, Afghanistan, and China. The fertile and densely populated plains of the lower Indus basin are home to some of the largest irrigation systems in the world. Irrigation practices account for over 90% of total water use here and largely depend on surface water originating in the mountainous upper Indus basin. Water demands in the lower Indus basin, in particular during the dry season, often exceed surface water availability. This results in numerous water scarcity issues and causes food production to structurally depend on the unsustainable use of groundwater. The Indus basin faces a rapidly expanding population and economic growth, which will result in a strong increase in the demand for both food and water. This means more food must be produced in the region, even though competition for irrigation water will increase. Climate change will in addition make downstream water availability less reliable and constrain food production.

These combined climatic and socioeconomic developments are likely to aggravate the existing trade-offs between water and food security. The Indus basin has therefore been designated as a climate change hotspot. Achieving the interlinked Sustainable Development Goals (SDGs) for water and food security (SDG2 and SDG6) here is highly challenging and requires urgent integrated action. This thesis aims to support long-term adaptation planning in the Indus basin by exploring drivers and trade-offs for future water and food security and by evaluating potential adaptation strategies. The main research objective is as follows:

- *To quantitatively explore how water management and food production in the Indus basin can be adapted to support both water and food security related Sustainable Development Goals in the face of climatic and socioeconomic changes.*

The research objective is addressed on the basis of three research steps that combine regional scenario building with high-resolution integrated modelling of interactions between hydrology, climate and agriculture. The research work is described in four chapters.

First, Chapter 2 addresses the lack of detailed quantitative scenarios for future resource security requirements under socio-economic development in the Indus basin. To this end, three Indus basin scenarios were developed by regionalizing existing scenarios of the global Shared Socioeconomic Pathways framework. The scenarios were made quantitative and spatially explicit using BasinPop, a novel tool to simulate future population distributions. The spatial scenarios were then used to quantify future water, food, and energy requirements in the basin. The results show that by 2080, basin-level water and energy security requirements may at least double and potentially triple compared to the current situation, while food requirements will also considerably increase. Migration and urbanization will lead to a spatial convergence of resource requirements around the largest cities in the basin. This means that the demand for water, food and energy in the Indus basin will increase, but in addition will also become more concentrated in space. Socio-economic development will therefore increases the complexity of the water-food-energy security challenges, and must thus be accounted for in adaptation planning.

Chapter 3 focused on quantifying the impact of future socioeconomic changes in the upper Indus basin on water availability downstream, in the lower Indus basin. These changes have received little scientific attention so far, as previous research work predominantly focused on

the effect of climate change on upstream-downstream linkages. The results demonstrate that future water use and the resulting pressure on water availability in the upper Indus basin will vary considerably across seasons and sub-basins. Water scarcity issues may appear in particular during the dry season, as present-day surface water demands are already relatively high compared to availability. In several transboundary sub-basins (Kabul, Jhelum), future water requirements may exceed availability during the critical winter months. This strongly reduces the outflow to downstream regions. The impact of growing upstream use on downstream per capita seasonal water availability in the lower Indus basin is compounded by downstream population growth. In the future, increasing water consumption in the upper Indus basin may thus cause local water scarcity issues and aggravate downstream water stress during the dry season. Water management in the Indus basin should consider the impacts of socio-economic changes in the upper Indus basin and anticipate increasing competition between upstream and downstream riparians.

The most important interactions between water availability and food production in the Indus basin are formed by irrigated agriculture and associated water use practices. In Chapter 4 the consequences for future water and food security objectives of three contrasting strategies for future agricultural development were examined. The results demonstrate that changes in the agricultural system aimed at food security can ensure future per capita food availability remains stable under population growth. However, this requires substantial additional irrigation water resources and will therefore worsen water stress in the lower Indus basin. Strategies for agricultural development focused on sustainable water management can conversely reduce water stress, but cannot maintain food self-sufficiency for the basin on the long-term. This suggests biophysical limits may exist for the capacity of agricultural system changes to simultaneously ensure sufficient food production and improve water security under continued population growth. Adaptation strategies that target both water and food SDGs must therefore combine agricultural development with other interventions that can mitigate their adverse trade-offs.

Agricultural system changes are explored further in Chapter 5 using a spatial adaptation pathways approach for irrigated wheat production. Wheat is a staple crop in the Indus basin and self-sufficiency in terms of wheat production is an important indicator for regional food security. In this chapter, a novel tool was developed to construct pathways that pursue objectives for both irrigation water savings and wheat production on the basis of spatially explicit adaptation options. The resulting pathways show that for the short-term, a combination of agricultural system changes and technical interventions can offer mutual benefits for water and food security. However, for the long-term it is uncertain whether pathways can reconcile both objectives. Pathways eventually run out of mutually beneficial adaptation options in high population futures and are forced to prioritize adaptation for either water or food security. The pathways demonstrate the degree to which long-term adaptation objectives are feasible in the Indus basin under a variety of future developments. From a methodological perspective, this chapter shows that spatial and multi-objectives pathways are better able to represent the contexts and challenges faced by adaptation planning at the regional level.

Lastly, in Chapter 6, the research steps are summarized and the main research objective is addressed. The synthesis highlights that the combined impact of climatic and socioeconomic changes will intensify pressure on water-food dependencies in all plausible futures. Improving water security (SDG6) requires irrigation water demands in the lower Indus basin to be brought into sustainable limits and in addition provide space to compensate for growing water use upstream and by other sectors. This must however be achieved without compromising future food production (SDG2). Extensive changes to agriculture and associated water management, in particular in the form of adaptation pathways, can provide considerable benefits for both SDGs. However, technical adaptation of irrigated agriculture alone may not be enough to reconcile water and food security on the long-term. Alternative adaptation directions that go beyond optimizing the current relations between water management and food production must therefore also be considered. This will likely increase dependencies with other sustainable developments objectives, such as energy security and economic development. In addition to technical interventions, more transboundary and intersectoral cooperation are therefore fundamental boundary conditions for robust and sustainable water-food adaptation in the Indus basin on the long-term.

Acknowledgements

This PhD journey of the last 4 years was filled with many highlights, such as visits to Spain, Kenya, and Pakistan, as well as having the opportunity to supervise thesis students and coursework. Yet, there were also times of isolation- especially during the COVID pandemic- with long weeks of (over)thinking and programming whilst stuck at home. Thankfully, there were always people I could count on throughout the last four year to make sure that, although alone, I never was lonely with my PhD. As I see it, completing a PhD is therefore far from an individual process or accomplishment! The many steps of researching, analyzing, and writing a thesis are, in reality, a team-effort and I am grateful to everyone who has supported me throughout this process. I would like to take this opportunity to express my sincere gratitude to a few of these people who have supported and guided me over the last four years.

First and foremost, I would like to thank my supervisors, Hester Biemans and Fulco Ludwig, for their guidance, expertise, and support. I feel very fortunate to have had such wonderful supervisors who not only shared their knowledge, but also gave me the freedom to explore my own research interests (and make my own mistakes along the way…). Even when our research ideas did not align, you were always available to critically discuss and reflect on my work and support me in further shaping my thoughts. This helped me to grow into an independent researcher with my own ideas and vision on our field of science.

Furthermore I would like to thank my colleagues at WSG. In particular Bregje, Spyros, Raffaele, Mengru and Maria, who, although not my supervisors, also provided me with much needed advice on how to navigate the often-frustrating, and sometimes nonsensical, world of academia. Your support kept me focused and helped me to make the right choices to keep steady progress these last four years. I would also like to thank the secretaries, Maartje and Natalja, for making life as a WSG employee much easier, and Carolien for being a pleasant chairholder. Above all, however, I want to thank the other PhDs of WSG, especially Hugo, Ilaria, Jessica, Meijun, Wout and Nancy who organized the PhD trip to Italy with me. Organizing this trip was the highlight of my PhD and it would not have been possible without such a good team. For similar reasons I would like to thank Sarra, Abbey and Cristina, who have become both my colleagues and friends over the years.

My gratitude also extends to the people of the SustaIndus project, who have been my collaborators and partners in research. Thank you for giving me the opportunity to work on this project. Special thanks go to my fellow PhDs, Khalid and Sanita. Your camaraderie and support have helped me navigate the ups and downs of the SustaIndus research project, especially during the COVID pandemic.

To conclude, I want to thank my family and friends, particularly my parents and Nicole, for your constant support, encouragement... but mostly for your willingness to listen to my seemingly endless stream of complaints and grumbles about work-related matters. Additionally, I want to extend my appreciation to Nicole's parents for providing me with a peaceful and sunny place to complete my thesis without distractions. Chimi the family dog was a great companion during this time. Finally, I want to thank my friends, who have provided me with much-needed laughter, support, and above all perspective throughout my PhD. You reminded me (many times) that, in the end, doing a PhD is 'just a job' and that work problems are often not all that significant when you zoom out a bit. Your support helped me maintain a healthy work-life balance and reminded me of the joys of life beyond academia.

About the Author

Wouter Smolenaars was born on October 8th 1994 in Nijmegen (Gelderland), the Netherlands. After graduating high-school, he started his Bachelor Landscape Architecture and Spatial Planning in 2013 at Wageningen University & Research in the Netherlands. For this bachelor, he specialized in Spatial Planning and Urban Environmental Management. The Spatial Planning bachelor focusses specifically on understanding the connections between ecology, soil, hydrology, cultural history, geography, economy and policy making in relation to the goals and needs of stakeholders in the present and on the long-term. This background sparked his interest in the interplay between spatial planning and water management, particularly in the context of climate change and adaptation planning.

Following his BSc graduation in 2017, he therefore continued his education with a Master's degree in International Land and Water Management at Wageningen University & Research in the Netherlands, opting for a specialization in Adaptive Water Management. This study program provides students with the knowledge and skills to analyze future challenges in water management and to propose and evaluate management strategies, policies, and innovations that can ensure resilient water systems. Through this study program, he developed an interest in the data-driven aspect of future water management challenges, which led him to take a minor in Hydrological Modelling. His MSc thesis centered on "Flood Risk and Adaptation Strategies for Soybean Production Systems on the Flood-Prone Pampas under Climate Change". This research work involved making a climate change impact assessment for soybean production on the basis of thresholds and indicators provided by local farmers in the Pampas region of Argentina.

After an internship as a climate adaptation and water management expert at the SWECO consultancy company, he graduated his MSc in 2019. He returned shortly after graduation to Wageningen University & Research to start his PhD in the SustaIndus project at the Water Systems and Global Change group. The following four years were dedicated to his PhD research, resulting in the completion of his PhD thesis entitled "Thirst for Food Security". After finishing his PhD, Wouter will stay at the Water System and Global Change group as a lecturer and continue to do research focused on climate change adaptation and sustainable development pathways.

List of Publications

First author publications

Smolenaars, W. J., Paparrizos, S., Werners, S., & Ludwig, F. (2021). Flood risk and adaptation strategies for soybean production systems on the flood-prone pampas under climate change. *Agronomy*, *11*(6), 1187, DOI: 10.3390/agronomy11061187.

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Smolenaars, W. J., Jamil, Dhaubanjar, S., M. K., Lutz, A., Immerzeel, W., Ludwig, F., & Biemans, H. (2023). Exploring the potential of agricultural system change as an integrated adaptation strategy for water and food security in the Indus basin. *Environment, Development and Sustainability*, DOI: 10.1007/s10668-023-03245-6.

Other publications

Dhaubanjar, S., Lutz, A. F., Gernaat, D. E., Nepal, S., **Smolenaars, W**.J., Pradhananga, S., ... & Immerzeel, W. W. (2021). A systematic framework for the assessment of sustainable hydropower potential in a river basin–The case of the upper Indus. *Science of the Total Environment*, *786*, 147142, DOI: 10.1016/j.scitotenv.2021.147142.

Paparrizos, S., **Smolenaars, W.J.**, Gbangou, T., Slobbe, E. V., & Ludwig, F. (2020). Verification of weather and seasonal forecast information concerning the peri-urban farmers' needs in the lower ganges delta in bangladesh. *Atmosphere, 11*(10), 1041, DOI: 10.3390/atmos11101041.

Conference contributions

Smolenaars, W. J., Jamil, Dhaubanjar, S., M. K., Lutz, A., Immerzeel, W., Ludwig, F., & Biemans, H. (2021). Quantifying Trade-Offs between Water and Food Security due to Future Land-Use Changes in the Indus Basin. *AGU Fall Meeting*, New Orleans, Louisiana, GC32C-07

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- Research in context activity: ‘ Organise a co-creation session with local policymakers in Pakistan to assess regional differences and preferences regarding the suitability of adaptation measures and land-use strategies’ (2022)

Other PhD and Advanced MSc Courses

- Supervising BSc & MSc thesis students, Wageningen Graduate Schools (2019)
- African roads to Sustainable Agroecology; Transdisciplinary Field Course, ETH Zurich & PE&RC (2022)
- Principles of Machine Learning: R Edition, edX (2020)

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- Basic Safety & Security, Centre for Safety and Development & Wageningen Academy (2019)
- Career orientation, Hertz(2022)

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- Course assistant in the MSc courses ‘WRM60309 Sustainable Land and Water Management’ (2020, 2021, 2022) and ‘SLM51306 Adaptation to Climate Change in Developing Countries’ (2021, 2022)
- Advisory Appointment Committee professor position Environmental Systems Analysis group (2020-2021)
- Organise PhD writing day (2021) & Organise PhD study week (2022)

Oral Presentations

- *Quantifying water vs food security* American Geophysical Union, Fall meeting, 13-16 December 2021, New Orleans, USA

SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

The research described in this thesis was financially supported by the Dutch Research Council (NWO Wotro - Project W 07.30318.002), the Interdisciplinary Research and Education Fund (INREF) of Wageningen University and Research, and Utrecht University.

Financial support from Wageningen University for printing this thesis is gratefully acknowledged.

Printed by proefschriftmaken.nl