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Sustainable Water Resources Management Strategies and its Implications in the Irrigated Areas of the Indus Basin of Pakistan

MUHAMMAD MUZAMMIL

Referees from the Justus Liebig University Giessen
Prof. Dr. Lutz Breuer
Prof. Dr. Jan Siemens

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Abstract

Pakistan's agriculture relies heavily on the Indus basin, where 90% of the land is cultivated under irrigated agriculture. Limited water resources, poor irrigation practices, and inadequate water management pose a serious threat to the country's food security and economy. Recently, the Government of Pakistan has been working to implement a national water policy aimed at promoting the sustainable use of water resources. The policy targets the adoption of sustainable water−saving strategies for future irrigation practices. In this dissertation, alternative water management strategies are evaluated, including replacing water−intensive crops with less water−intensive ones and implementing improved irrigation technologies to replace less efficient surface irrigation methods. Furthermore, the impact of these alternative water management strategies is also investigated under climate change Representative Concentration Pathways (RCP2.6 and RCP8.5). The results show that up to 35% of water use can be reduced by using optimal cropping patterns and up to 50% by using both optimal cropping patterns and improved irrigation technologies under current climatic conditions (baseline scenario). While in the climate change scenarios, water consumption could be restrained by up to −3% compared to the status quo through the adaptation of alternative cropping patterns. Additionally, the results show that future water consumption under climate change could even be further decreased by up to −19% through the collective implementation of improved irrigation technologies and optimized cropping patterns. In a follow-up study, the site−specific greenhouse gas emissions of CO_2 associated with groundwater pumping, irrigation system operation, and bicarbonate extraction from groundwater are analyzed. Additionally, the associated costs and effects on groundwater depletion are assessed, assuming that yields remain stable. Various energy sources, such as solar power, are incorporated into the scenarios for improved irrigation technologies. Results indicate that a reduction in net CO_2 emissions is only possible via the extensive use of solar−powered systems, where net CO_2 emissions can decrease by up to 81%. All improved irrigation technologies result in increased irrigation costs but reduced groundwater depletion. If all scenarios are considered concerning the sustainability aspects examined, the solar system is by far the best option.

Table of contents

List of figures

List of figures in supporting information

List of tables

List of tables in supporting information

1 Extended Summary

1.1 Introduction

Agriculture is one of the dominant sectors in Pakistan's economy, supporting approximately 22% of the gross domestic product (GDP). It provides food for the growing population and supplies raw materials, especially cotton for the textile industry (Raza et al., 2012). Agricultural production primarily depends on irrigation due to the semi–arid to arid characteristic of the plain (Ahmad, 2007). Surface water originates from the Indus basin, which comprises five tributaries: Indus, Chenab, Jhelum, Sutlej, and Ravi (Qureshi et al., 2008). The combined average annual discharge of all tributaries in Pakistan is about 157 km^3 with 85% flowing in summer and 15% during winter (Cheema and Bastiaanssen, 2010).

The Indus basin irrigation system of Pakistan is the world's largest irrigation network consisting of 46 canals with a total length of 58,000 km and 1.6 million km length of watercourses irrigated to about 17 million ha (Wescoat Jr et al., 2000). About 100% of cash crops and 90% of food crops harvest along the command area of this network (Ringler and Anwar, 2013). The Indus basin irrigation system was designed approximately 100 years ago in the British era for low cropping intensity (60–80%) to ensure protection against famine (Jurriens, 1996). Over time, cropping intensity has increased by up to 172% to meet the growing population's food demand (Malik et al., 2009). Consequently, surface water now covers only 40–50% of the irrigation requirements. Farmers use groundwater as a supplementary source to compensate for the deficit in water supply, especially in the Punjab province (Shakir et al., 2010). While the trend of groundwater pumping is comparatively less in the Sindh province due to high concentration of salinity in the shallow aquifer (Cheema et al., 2014). Qureshi et al. (2010) reported that about 70% of irrigated areas of Pakistan are practiced with the conjunctive use of groundwater along with surface water. Groundwater is a prime source of irrigation for the farmers of the middle or tail of the watercourses and watercourses that are located end of the distributaries or distributaries that flow during rainy seasons (Mekonnen et al., 2016). This ultimately leads to groundwater depletion due to unsustainable pumping (Cheema et al., 2014). Wada et al. (2010) reported that Pakistan has been included in those countries where the unprecedented groundwater abstraction rate exceeds the natural groundwater recharge. As a consequence, aquifer recharge is less about 15% than the groundwater withdrawal in agricultural areas (Basharat, 2016). Despite the existing intensive groundwater pumping trend, the government of Pakistan provides subsidized electricity to farmers for pumping, imposing further pressure on groundwater resources (Qamar et al., 2018). Tellez Foster et al. (2018) reported that electricity subsidies on groundwater pumping is a major challenge for water managers in Pakistan as this issue is socially crucial when a large number of peoples get financial benefits.

In addition to water availability challenges, the quality of irrigation water is deteriorating due to increasing salinity. Salt concentration arises from salt pockets naturally present in the aquifer, and the Indus Rivers contribute an additional 16.5 million t of salts per annum in the basin (Qureshi et al., 2008). Groundwater salinity ranges 0.5–4.5 dS m^{-1} in the upper basin to up to 9 dS m^{-1} in the lower Indus basin (Muzammil et al., 2020). The extent of salinity is higher on the lands located at the tail of the distributaries where the drainage conditions are poor and saline shallow groundwater exist (Bhutta and Smedema, 2007). The World Bank reported that saline irrigation practices in Pakistan have affected about 23% of irrigated areas with soil salinity (Qureshi, 2018).

Despite the poor state of water resources in Pakistan, inefficient irrigation methods such as flood and furrow irrigation are commonly employed throughout the basin, resulting in irrigation efficiencies of less than 50% (Rizwan et al., 2018). Therefore, a huge water volume is lost in fields due to evaporation and deep percolation (Pervaiz, 2010). Pakistan has already crossed the threshold limit of water scarcity (1000 m^3/person/year) due to these poor irrigation practices and it is feared that it will even fall below the level of absolute water scarcity (500 m^3/person/year) in the next decade (Falkenmark, 1989; Muzammil et al., 2020). On top of these challenges, Pakistan's agriculture also have severe future climate change threats (Muzammil et al., 2023). Pakistan is one of the world's few countries that are either more vulnerable to climate or have been affected significantly by climate events (Abid et al., 2016). Studies revealed that future irrigation requirements could increase at the climate change hotspots, placing further burden on water resources (Gul et al., 2022; Saddique et al., 2022). Therefore, sustainable water management has become a challenge for policymakers and water managers in Pakistan, as climate change and a growing population continue to affect water availability and food security (Ahmad et al., 2019; Basharat, 2014). In the current scenario, the government of Pakistan has introduced a national water policy to tackle water scarcity challenges related to food security. The policy aims to foster the development of sustainable water–saving strategies for future irrigation practices.

The sustainable water use in irrigated agriculture is often feasible through the efficient utilization of available resources, technical improvements, and the development of new agricultural management scenarios (Cheng et al., 2022; Horne et al., 2018). In the past, various water management approaches have been recommended to save water, such as soil mulching (El–Beltagi et al., 2022), conservation tillage (Ali et al., 2017), deficit irrigation (Costa et al., 2007), irrigation scheduling (Carucci et al., 2023), and growing drought–resistant crops (Luo et al., 2019). Multsch et al. (2017) assessed water management strategies for Saudi Arabia, suggesting that a substantial amount of water could be saved by replacing fodder with cereal and vegetable crops in irrigation agriculture. Davis et al. (2017) demonstrated that India could enhance crop production and improve water consumption by adapting crops, implementing crop rotations, and targeting new irrigation districts. Ghaffar et al. (2022) anticipated that farmers should adopt climate–resilient technologies and drought–resistant crops to mitigate the negative impact of climate change on water resources.

This study focuses on evaluating water management strategies, including substituting high-water-demanding crops with low-water-demanding crops and replacing the current irrigation method (surface irrigation) with improved technologies such as drip and sprinkler irrigation. Studies show that a significant amount of irrigation water could be saved by replacing water intensive crops with low delta crops where water resources are limited or depleting rapidly. For example, Huang et al. (2012) studied the impact of cropping pattern modification on blue water use in the Beijing metropolitan areas as a result a substantial amount of water was saved by a transition from cereal to vegetable crops. Nouri et al. (2020) reported that water productivity increases and blue water scarcity could be reduced by changing cropping patterns in the Upper Litani Basin of Lebanon. Fan et al. (2022) showed that optimal cropping patterns was conducive for sustainable use of irrigation water in the dryland of Northwest China. In addition to alternative cropping patterns, the improved irrigation technologies have also potential to achieve water security and unreliable water supply challenges (Chaudhry and Garg, 2019; Dwijendra et al., 2022). Despite the water saving benefits across the world, the impact of these technologies varies from region to region due to dissimilarities in cost benefits and off–farm environmental impact (Jordan et al., 2021; Solomon and Ketema, 2015). Studies reveal that conducting an economic evaluation is a crucial process in assessing the feasibility of any project. Osei et al. (2023) evaluated the economic impact of conservation tillage in a Northeastern Iowa County and concluded that no–tillage is not profitable for corn and soybean crops. Rodrigues et al. (2012) estimated the economic impact of high–efficiency irrigation technologies in Brazil and determined that the net benefits of drip and sprinkler irrigation are less than the actual cost of the system. Similar to the economic impact, irrigation projects also have environmental implications at the basin or field level. For example, Daccache et al. (2014) reported that improved irrigation technologies have the potential to increase efficiency, but they can also lead to increased greenhouse gas emissions due to additional energy usage compared to surface irrigation (gravity–fed). Mojid and Mainuddin (2021) indicated that although improved irrigation systems reduce agricultural water consumption, they negatively impact groundwater dynamics as recharge decreases due to less percolation compared to surface irrigation (Mojid and Mainuddin, 2021). Chen et al. (2020) assessed the environmental impact of water–saving irrigation systems (drip and sprinkler irrigation) in northern China, the results show that the water footprint was reduced while the carbon footprint was increased.

In this dissertation, water consumption is estimated based on the usage of green, blue, and grey water sources. Additionally, the impact of water-saving strategies on water use is assessed, namely: (i) identifying and evaluating optimized cropping patterns by replacing high water-intensive crops with less water-intensive ones, and (ii) investigating the impact of improved irrigation technologies (drip and sprinkler irrigation) compared to the status quo method (surface irrigation). In the next step, future water consumption is estimated by considering climate change scenarios and studying the impact of water–saving strategies in the future. Further, the economic and environmental impact of improved irrigation technologies is also investigated, where the site–specific greenhouse emissions of CO_2 associated with groundwater pumping, irrigation system operation, and bicarbonate extraction from groundwater are estimated. Additionally, associated costs and effects on groundwater depletion are calculated, assuming that yields remain stable.

1.2 Objectives of the dissertation

The aim of this dissertation is to develop strategies for achieving sustainable use of water resources in the Indus basin by evaluating different water management patterns. Three following objectives are addressed in separate chapters:

1) to develop water resources management strategies for irrigated agriculture in the Indus basin of Pakistan (*Chapter 2*)

To achieve sustainability in water use, several straightforward cropping scenarios are developed by replacing water–intensive crops with less water–intensive crops. The impact of the same cropping scenarios is then investigated by replacing the status quo irrigation method (surface irrigation) with improved irrigation technologies (drip and sprinkler irrigation).

2) to identify climate change adaptation strategies for sustainable water management in the Indus basin of Pakistan (*Chapter 3*)

The second objective focuses on the impact of climate change on crop water requirements. It demonstrates the potential change in water demand in the Indus basin under different scenarios, ranging from business as usual (RCP2.6) to the worst climate change scenario (RCP8.5). Sustainable agricultural production pathways are developed by intelligently combining cropping patterns with changes in irrigation efficiency and smart water use in the region, considering various climate change projections.

3) to assess the economic and environmental impact of sustainable future irrigation practices in the Indus basin of Pakistan on water resources (*Chapter 4*)

To attain the third objective, further aspects of sustainability are considered by (i) estimating the CO_2 emissions from the operation of the irrigation system (using different energy sources) and from the extraction of carbonate from groundwater, which leads to carbon dioxide emissions, (ii) quantifying the associated irrigation costs, and (iii) assessing the resulting groundwater depletion.

1.3 Methods & approaches

1.3.1 Study area

The study area is the irrigated plain of the Punjab and Sindh provinces located between latitude 24.14° to 34.46° north and longitude 67.41° to 74.68° east (Figure 1.1). The study area covers approximately 17 million ha where the topography of the plain descends from 540 m (north) to 4 m (south) above mean sea level. The plain experiences an arid to semi-arid climate characterized by complex hydrological variations resulting from spatial and temporal changes in rainfall, temperature, and land use. The potential evapotranspiration varies from 1,200 to 2,050 mm from the upper (north) to the lower basin (south). The maximum temperature ranges from 34−44°C in summer to 20−28°C in winter. The average annual rainfall amounts to 380 mm, of which 80% occurs during the summer season. There are two cropping seasons, Rabi (wet) and Kharif (dry). The Rabi season runs from October to March with wheat as the dominant crop, while the Kharif season runs from April to September, and is dominated by cotton, rice, and sugarcane.

Surface water originates from the five tributaries (Indus, Chenab, Ravi, Jhelum, and Sutlej) and is delivered to fields from a network of main canals, branch canals, and watercourses. The provincial government distributes surface water to farmers and collects water charges based on the size of individuals' landholdings. Water charge rates and patterns vary among provinces; for instance, the Punjab government collects water charges at a flat rate per hectare, while in Sindh, water charges depend on crop types, considering the water intensiveness of the crops. To pump groundwater in the basin, both public and private tubewells operate using diesel engines and electricity. The government provides subsidies on electricity to farmers, and while diesel−operated tubewells are more common due to their low initial investment, they constitute 87% of the total tubewells. Crops are irrigated mainly by surface irrigation (i.e., flood and furrow irrigation) with a rather low efficiency of 40−50%. Improved irrigation technologies (i.e., drip and sprinkler irrigation) are installed in a limited area (less than 50,000 ha) under a subsidized Punjab Irrigated

Agriculture Productivity Improvement Project (PIPIP) project of the World Bank and the government of Punjab.

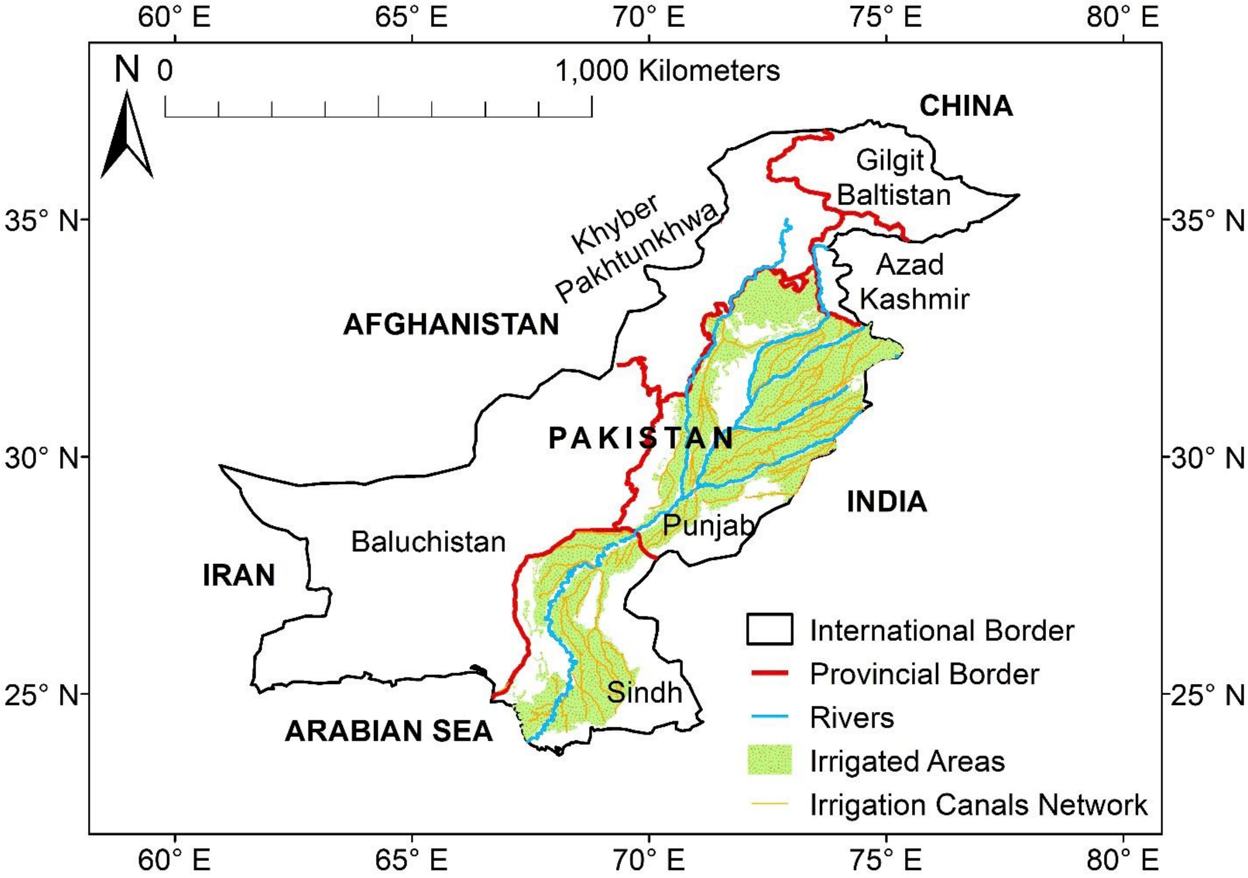

Figure 1.1 Study area of the Punjab and Sindh provinces in the Indus basin of Pakistan.

1.3.2 Water footprint assessment

A water accounting approach is used to demonstrate water resources concerning water availability and consumption (Vardon et al., 2007). This approach serves as decision–support information to achieve sustainability in water balance, improving water use efficiency, allocation of water resources, and policy development (Bassi et al., 2020). The water footprint is used as a performance indicator that quantifies water consumption as a production factor (Hoekstra et al., 2011). It describes the quantity of water required to produce the commodities, goods, or services for persons, communities, or delimited areas. Water footprint is composed of three components according to the water sources, i.e., green water comes from precipitation, blue water deals with irrigation water such as surface water and groundwater, and grey water is required to dilute the salt concentration in the soil. In the past, the water footprint has been used to evaluate water management approaches and strategies for water governance, amongst many other objectives, such as product foot printing. For example, Novoa et al. (2019) evaluated the agricultural water footprint of Chile to improve water management, concluding that WF assessment is very helpful in managing water resources as it provides a quantitative basis for water consumption. Le Roux et al. (2018) reported that the water footprint nexus is a popular concept for resource management as it compares green and blue water consumption versus water availability. Bigdeli Nalbandan et al. (2023) used the water footprint accounting framework to study the new water management policies in the Tashk–Bakhtegan Basin of Iran. They found that replacing water–intensive crops has a positive impact on surface water and groundwater sustainability. The Indus basin is a very large plain, where there is a large variation in the climate, land use, and available water sources. Hence, this study uses the spatially explicit water footprint as a performance indicator to evaluate the impact of alternative water management strategies according to the sources of water use.

1.3.3 SPARE:WATER model

Over the past decade, Multsch et al. (2013) developed, applied, and improved the SPARE:WATER water balance model, a spatial decision support system for crop and irrigation water demand assessment and agricultural water footprint accounting. SPARE:WATER is an open–source product for the simulation of spatially explicit agricultural water demand based on the FAO56 concept originally developed by Allen et al. (1998). The model is integrated in a Geographical Information System (GIS) and runs via the graphical user interface. SPARE:WATER calculates the water footprint according to the guidelines of Hoekstra et al. (2011). It allows the estimation of the three main components of the water footprint, i.e., green water (provided by precipitation), blue water (added by surface water and groundwater via irrigation), and grey water (the amount of water required to dilute polluted water to specified water quality standards). In the case of agriculture, the latter is estimated as the amount of water required to leach salts and represents the dominant grey water use in irrigated agriculture. The leaching requirement is calculated according to the salinity tolerance of each crop as suggested by FAO (Ayers and Westcot, 1985). For example, cotton has a higher salinity tolerance limit (7.7 dS/m) than rice (3 dS/m), resulting in a higher leaching requirement for rice as part of field preparation. Further, SPARE:WATER considers cropping patterns, irrigation methods, and irrigation efficiency and can be applied according to the needs or demands of water managers, scientists, and policymakers.

SPARE:WATER has been used in several large–scale applications, including Saudi Arabia (Multsch et al., 2017), Brazil (Multsch et al., 2019) and the Nile Basin (Multsch et al., 2017). In this study, the SPARE:WATER model is enhanced and applied to conduct an economic and environmental impact assessment of alternative management strategies. It estimates site-specific irrigation costs, groundwater anomalies, and CO_2 emissions under different cropping and irrigation scenarios. Additionally, various energy source scenarios, including solar power combined with changes in irrigation methods, are explored. The optimized modeling framework was developed in Python using the Scipy package. In addition to standard SPARE:WATER modeling inputs such as irrigation requirements, harvested area, and crop water consumption, this study also incorporates groundwater levels, energy consumption for water pumping, water prices, energy costs, and fuel consumption and emission factors.

1.4 Main results

1.4.1 Evaluation of water management strategies

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Water footprint is a widely used performance indicator for water management and policy implications. In this study, SPARE:WATER is used to calculate Pakistani agriculture's spatial and temporal crop water footprint and regional water consumption from 1997–2016 to produce crops (Muzammil et al., 2020). Further, the impact of water management strategies on water savings potential using SPARE:WATER was investigated. In the first step, a set of simple cropping scenarios is developed to optimize and balance cropping patterns by replacing crops with low water use efficiency with more efficient ones. In the second step, the contribution of improved irrigation technologies (such as drip and sprinkler irrigation) is evaluated to assess water savings compared to the status quo irrigation method (surface irrigation). Additionally, the increased demand for grey water is considered when efficient irrigation methods replace inefficient ones. This results from reduced water use and therefore reduced leaching of salts from the soil.

Our results show that the average water consumption in the study area is 182 km^3 yr^{-1}, of which 75% is allocated to blue water, 17% to green water, and 8% to grey water, respectively. Sugarcane, cotton, and rice (cash crops) are the predominant crops grown during the Kharif season, while wheat is the main crop during the Rabi season. Among these, sugarcane is the most water-intensive crop, followed by rice and cotton. Despite covering only 36% of the annual harvested area in the Kharif season, these three crops account for approximately 57% of the annual water footprint (WF_{area}). Conversely, wheat, cultivated on 39% of the annual harvested area in the Rabi season, consumes only 24% of the annual WF_{area}. In scenarios, adjusted cropping patterns have shown the potential to reduce annual water use by up to 35% by replacing water-intensive cash crops (such as sugarcane, cotton, and rice) with less water-intensive maize crops under the current irrigation settings. In addition to the ultimate scenario, substituting sugarcane with cotton and substituting sugarcane and rice with cotton represent more balanced cropping patterns that result in a reduction of water consumption by 13% and 18%, respectively. Based on these findings, it is recommended to cultivate cotton in the harvested area of all cash crops if the complete termination of cash crops is not feasible. Furthermore, the collective adoption of optimal cropping patterns alongside improved irrigation technologies could reduce water consumption up to 50%.

1.4.2 Climate change adaptation strategies for sustainable water management

This work is published as:

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Future water demand and the impact of water-saving strategies are evaluated in the Indus basin of Pakistan under two representative climate change pathways (RCP2.6 and RCP8.5). The RCPs are evaluated using the regional climate model REMO2015, identified as the best-fitting model for the current situation in a preceding model comparison conducted using Taylor diagrams. A regression method is employed to project the future cropped area, while the Degree Days (GDDs) concept is utilized to assess changes in the growing season due to climate change. The harvested area increased for all major crops compared to the status quo. However, the largest increase is observed for wheat (4.8 Mha), followed by cotton (2.2 Mha), rice (1.8 Mha), sugarcane (0.5 Mha), and maize (0.3 Mha). While the GDDs approach is considered appropriate for determining the vegetation period affected by climate change, particularly when crops mature earlier due to rising temperatures. The vegetation period is estimated by accumulating Growing Degree Days (GDDs). A crop reaches maturity when the seasonal accumulated GDDs reach a required level. The vegetation period for crops reduced by 6−16 days under RCP2.6 and by 8−18 days under RCP8.5 pathways.

In a first step of the study, the future water consumption was projected for climate change scenarios RCP2.6 and RCP8.5 at the status quo irrigation settings. Results with no change in the harvested areas indicate that water consumption increased by up to 11% under RCP2.6, while it increased by up to 7% under RCP8.5. Future water consumption for the projected harvested area increased substantially by up to 73% under RCP2.6, and showed again a slightly lower increase of up to 68% under RCP8.5. In a second step, the future water consumption was estimated by replacing the status quo irrigation method with improved irrigation technologies. The results indicate that average water consumption with no change in the harvested area decreased by up to -16% under RCP2.6, and up to -18% under RCP8.5. Again, the average water consumption still increased with projected surplus in the harvested area by up to 29% under RCP 2.6 and 23% under RCP8.5, respectively.

In the final scenario analyses, the water−intensive cash crops (i.e., sugarcane, rice, cotton) were replaced with less water−demanding crops such as maize by considering status quo irrigation settings and alternative improved irrigation technologies. The results indicated that the water demand could be limited to −3% by only replacing the water−intensive cash crops, and even lowered to −19% by also implementing improved irrigation technologies.

The overall findings indicate that RCP2.6 exhibited greater vulnerability than RCP8.5 in terms of water use, primarily because the growing season was shorter under RCP8.5. The reduced growing period led to decreased crop water requirements. However, water consumption is projected to increase linearly in both RCPs due to the combined impact of expanding harvested areas and climate change.

1.4.3 Economic and environmental impact of improved irrigation technologies

This work is published as:

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The previous section highlighted that a significant amount of water could be conserved in Pakistan by replacing the status quo irrigation practices with improved irrigation technologies (Muzammil et al. 2020). However, the choice of irrigation technologies and their associated energy requirements have diverse environmental and economic implications. To investigate the sustainability of improved irrigation technologies compared to the status quo in the Indus basin of Pakistan, a coupled economic-environmental modeling framework has been developed. This framework, implemented in Python using the Scipy package, explores three key aspects of sustainability (Muzammil et al., 2021). Firstly, it analyzes the site-specific greenhouse gas emissions of CO_2 associated with groundwater pumping and bicarbonate extraction from groundwater. In the case of bicarbonate extraction, CO_2 is emitted if groundwater is depleted, while CO_2 is sequestered in the aquifer in cases of rising groundwater levels. Secondly, the associated costs and impacts on groundwater depletion is estimated, assuming that yields remain stable. Finally, various energy sources are considered in the scenarios, such as subsidized electricity and decentralized solar power, to identify the optimal energy supply for irrigation in the Indus basin.

The results indicate that about 4.12 Mio t/yr of CO_2 is emitted under status quo conditions, of which 96% is due to energy consumption from groundwater pumping and 4% from bicarbonate extraction. In the improved irrigation scenarios, CO_2 emissions from groundwater pumping could be reduced by up to 60% due to a decrease in groundwater consumption resulting from the use of irrigation technologies. However, additional energy is required to operate the improved irrigation systems, such as drip irrigation for row crops and sprinkler irrigation for field crops, compared to the mainly gravity-fed status quo. As a result, the overall net CO_2 balance for the electricity and diesel engine scenarios worsens by 165% and 410%, respectively. Future reductions in net CO_2 emissions and improvements in water use are only possible through extensive use of solar−powered systems, which can reduce net CO_2 emissions by up to 81%. All improved irrigation technologies result in increased irrigation costs but reduced groundwater depletion. When all scenarios are considered in terms of the sustainability aspects examined, the solar system is by far the best.

1.5 Research outlook

Nowadays, many people are concerned about the potential water demand arising from the growing population's increasing food and energy needs. The agricultural water demand, for example. is expected to increase by up to 55% by 2050 due to the negative impact of climate change and the growing population (de Fraiture and Wichelns, 2010). The water availability pattern is changing worldwide due to climate change, leading to water scarcity and environmental concerns (Pfister et al., 2011). Specifically, the water resources of developing countries are under significant pressure, where water monitoring and governance are unreliable—resulting in substantial water loss due to inefficient practices and inadequate infrastructure (Pfister et al., 2011). In many cases, water managers focus on achieving short−term water−saving goals without considering the long−term environmental and economic impact, which are not sustainable.

Pakistan is among those countries, where water resources are limited and depleting very rapidly. It is due to insecure water supply, inefficient irrigation methods, and unsustainable groundwater pumping (Muzammil et al., 2020). An increasing food demand of the growing population and climate change further impose pressure on water resources (Saddique et al., 2022). Studies show that the status quo trend of water consumption is leading the country toward absolute water scarcity (Ringler and Anwar, 2013; Wescoat Jr et al., 2000).

This dissertation examines various aspects of crop water use and irrigation efficiency in the Indus Basin of Pakistan utilizing the SPARE:WATER spatial decision support system. The first chapter evaluates water-saving strategies by optimizing cropping patterns and replacing the current irrigation method (surface irrigation) with improved technologies such as drip and sprinkler irrigation. The findings suggest significant water savings through the adoption of optimized cropping patterns and the use of improved irrigation technologies. The second chapter examines the impact of climate change on crop water requirements under current conditions and with optimized cropping scenarios. Results indicate a potentially dramatic increase in water demand in the Indus Basin if current practices persist. To address this challenge, sustainable agricultural production pathways are proposed, integrating smart water management strategies that combine optimized cropping patterns with enhanced irrigation efficiency to mitigate the effects of climate change (Muzammil et al., 2023). The third chapter delves into additional dimensions of sustainability by estimating CO_2 emissions arising from the operation of irrigation systems, accounting for different energy sources, and from carbonate extraction from groundwater. Furthermore, the chapter quantifies associated irrigation costs and the resulting depletion of groundwater resources (Muzammil et al., 2021).

The analyses conducted thus far reveal significant potential for both technical and agronomic optimization within Pakistan's irrigated agriculture. These optimizations have the potential to reduce water consumption while simultaneously enhancing CO_2 emissions and economic performance. However, food security and sovereignty aspects have not been considered in the existing scenarios. A reorientation of agriculture is imperative, particularly in light of a growing population and the escalating impacts of weather extremes, including droughts and floods, on Pakistan's agricultural sector. This reorientation should consider site-specific conditions such as soil quality, climate, and the availability of irrigation water, while also addressing national food needs. With regard to the latter, cash crops, which often have high water requirements, do not contribute to the national food supply. At the same time, it is important to consider the economic livelihoods of smallholder farmers. Smallholder farmers cultivate around 90% of the agricultural land in Pakistan and therefore produce most of the country's cash crops. Therefore, the needs and potential of smallholder farmers should be a primary consideration when developing future land use scenarios in the context of climate change.

In the broader context, it is recommended to develop a method for the sustainable assessment of future irrigated agriculture. This method should incorporate a multi-objective decision module directly linked to crop water demand estimation, capable of considering a comprehensive list of constraints previously investigated. Multi−objective decision criteria to be considered in future water resource management must not only include water quantity, which has been the most commonly used criterion in irrigation optimization studies. Other aspects, such as water quality (e.g., nitrogen pollution or pesticide leaching), other greenhouse gas emissions (CH_4 emission in wet rice or N_2O emissions from fertilizer application), fossil fuels versus renewable energy use for groundwater pumping, the nutritional value and protein supply from food commodities, but also economic aspects such as local markets, labor, and income will need to be taken into account when evaluating future irrigation scenarios. However, for such complex decisions, a multi-criteria decision support tool needs to first of all include all these aspects and secondly be capable of considering multiple constraints during the decision making process. Multsch et al. (2017) proposed a method based on the simplex algorithm to select preferable cropping patterns given local resources limitation. However, their approach is based on a posteriori selection of best cropping patterns, disregarding interactions of constraints.

2 Water Resources Management Strategies for Irrigated Agriculture in the Indus basin of Pakistan

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2.1 Introduction

Irrigated agriculture in Pakistan is mostly associated with the Indus plains where 100% of cash and 90% of food crops depend on irrigation (Ringler and Anwar, 2013; Yang et al., 2016). Surface water resources of Pakistan originate from the Indus basin that consists of five tributaries (Indus, Chenab, Jhelum, Sutlej, and Ravi). The average flow of these tributaries are 171 km^3 yr^{-1}. Approximately 75% of the water is diverted to the canal network for irrigation. Of the available water, only 43 km^3 (34%) reaches the farm's gate. Large amounts of the water is lost in channels due to poor conveyance efficiency of the irrigation system (Bandaragoda and Rehman, 1995; Mekonnen et al., 2015). The effective rainfall adds another 16 km^3 yr^{-1} water to the basin (long−term average) (Ahmad, 2007; Ringler and Anwar, 2013). However, the combination of surface water and rainfall cannot satisfy crop water demands of the plain (Qureshi et al., 2010). Therefore, a vast amount of groundwater is used to achieve 40−60% of the irrigation needs (Cheema et al., 2014; Sarwar and Eggers, 2006). The unsustainable rate of groundwater pumping results in a decline of the groundwater table. The government of Pakistan reported that the groundwater table of 5−15% of the irrigated areas has dropped to inaccessible depths, mainly in the Punjab province (Bank, 2002; Qureshi et al., 2008). Additionally, groundwater quality is deteriorating, mainly due to increasing salinity. The main sources of salinity are saline pockets that existed naturally in the shallow aquifer and the Indus rivers system which added about 16.6 million tons salts annually in the basin via irrigation (Qureshi, 2011). While salinity varies between 0.5−4.50 dS m^{-1} in the upper part (Punjab province), it drops down to 9 dS m^{-1} in the lower part of the Indus basin (Sindh province). Qureshi et al. (2010) report that for 23% of the irrigated area in Punjab, and even 78% of the area in Sindh are affected by poor water quality, even though they are not reporting how they did define "poor water quality". On top of the water quality issues, Pakistan has crossed the threshold limits of water scarcity of 1,000 m^3/capita/year and is likely to reach even absolute water scarcity conditions (<500 m^3/capita/year) by 2035 (Briscoe and Qamar, 2005; Falkenmark, 1989). Therefore, it has become a big challenge to ensure water security and related to this, food security, for the growing population, keeping in mind that climate change is further impacting crop production wand water availability (Kirby et al., 2017).

Recently (2018), the government of Pakistan has established a water policy to overcome water scarcity (National Water Policy, 2018). This policy aims at developing future strategies and action plans through the concept of *more crop per drop*. Various management practices have been proposed to support this concept. Examples include deficit irrigation to improve water productivity (Galindo et al., 2018), irrigation technologies to reduce field irrigation losses (Evans and Sadler, 2008), cultivation of drought–resistant crops (Hu and Xiong, 2014), substitution of water–intensive crops with less water demanding crops (Davis et al., 2017), soil mulching to preserve soil moisture (Kader et al., 2019), or conservation tillage to enhance water use efficiency of the crops (Ali et al., 2017). In this study, we focus on the evaluation of two alternative strategies, which have been also discussed in water policy as prospective options, i.e., substitution of high water–intensive crops with less water demanding crops and shifting traditional irrigation practices (surface) to more advanced irrigation technologies.

Water footprint (WF) assessment can be used to investigate alternative management strategies for water governance (García Morillo et al., 2015; Mali et al., 2017). The WF is defined as the volume of water used to produce goods and services by individuals, communities or delineated areas such as watersheds or nations. The WF consists of three main components according to the sources of water use. In agriculture, green water is provided from precipitation. Blue water is the amount of freshwater taken from natural resources such as surface water or groundwater and supplied via irrigation. Grey water is the amount of water needed to dilute pollutants (Hoekstra et al., 2011), for example to wash out salts from the root zone to facilitate crop growth or to reduce harmful chemical concentrations in recharging groundwater. Nouri et al. (2019) studied the impact of soil mulching and drip irrigation through WF assessment in the upper Litani basin of Lebanon and concluded that these alternatives practices have the potential to reduce the WF of all major crops, but their benefits are insufficient to control the overconsumption of water. Cao et al. (2014) analyzed water−saving strategies to improve water use efficiency of irrigated grain crops in China by using the WF assessment approach and proposed that the government should invest in advanced water−saving technologies to reduce the pressure on water resources in order to increase the food security of the country. Multsch et al. (2017) evaluated various cropping patterns and irrigation technologies in Saudi Arabia and recommended that substitution of fodder crops with vegetables and cereal crops have a great potential to reduce water consumption in the country. Tsakmakis et al. (2018) investigated the impact of irrigation technologies on cotton crop through WF assessment in northern Greece and confirmed that drip irrigation technology has a high potential to save the loss of unproductive water compared to sprinkler irrigation.

In this study, we use the SPARE:WATER model (Multsch et al., 2013) to estimate the WF of crops in Pakistan and evaluate a number of water−saving strategies. SPARE:WATER is a spatial decision support system to estimate site−specific crop water requirements. It follows the principles to calculate the crop water requirement during the vegetation period in accordance with the FAO56 guidelines (Allen et al., 1998). The SPARE:WATER package has been used in a number of studies to assess the regional water footprint and crop water requirement (Multsch et al., 2014). Since salinity of irrigation water has a high impact on soil salinization and crop production, we consider the leaching requirement as the dominant component of the grey water fraction of the WF as discussed by (Multsch et al., 2013). Leaching requirement in this regard is the water needed to dilute the salts present in the irrigation water and the soil.

The objectives of the current study are: 1) to develop alternative cropping patterns for improving the WF, considering the salinity of the irrigation water as it affects the leaching requirement, and 2) to investigate the impact of improved irrigation technologies on water savings. The objectives are investigated in two different steps. The WF is estimated for crops and the entire region in the first step, whereas alternative cropping patterns are evaluated in the second step by considering two different irrigation settings, i.e., existing traditional irrigation methods and improved irrigation technologies.

2.2 Materials and methods

2.2.1 Study area

This study focuses on the irrigated zones of the Punjab and Sindh provinces (24.03° to 34.10°N, 67.40° to 74.69°E), which cover approximately 17 million hectares of the Indus basin within Pakistan (Figure 2.1). The surface topography is characterized by hills of up to 540 m a.s.l. in the north and flat lowlands of up to 4 m a.s.l. in the south. The basin has a semi−arid to arid climate with significant spatial and temporal variation in temperature and rainfall. The summer season extends from April to September with average maximum temperatures (Tmax) of 34–44 °C. The winter season is short from December to February with Tmax 20–28 °C. Average annual rainfall of 372 mm (1997–2016) peaks in the summer season. There are two common cropping seasons called Kharif (April−September), dominated by sugarcane, cotton, rice, and fodder crops as well as the dry Rabi season (October–March), in which mainly wheat and fodder crops are grown. Sugarcane, cotton, and rice are grown as cash crops while wheat is cultivated to meet the domestic food demand.

The Indus River system provides irrigation water through a network of canals, distributaries, and watercourses. Groundwater is used in areas as a primary source where there is no access to canal water or where the quantity of surface water is insufficient for irrigation. In all other areas, groundwater is used as a secondary source of irrigation to meet the crop water requirements. Groundwater is pumped from small private tube wells, which are easy to install and operate due to the cheap availability of drilling machinery at local level and the subsidized costs of electricity for farmers. However, this only applies as long as the groundwater level does not sink too far. Water is applied to fields through surface irrigation in furrows (e.g., cotton, sugarcane) or as flood irrigation (e.g., rice, wheat and fodder crops) with low application efficiencies of 45 to 60 %. High−efficiency irrigation systems (drip and sprinkler irrigation) are only installed at a small scale (50,000 ha) through a subsidized project of the World Bank and the government of Punjab (PIPIP 2012–2021).

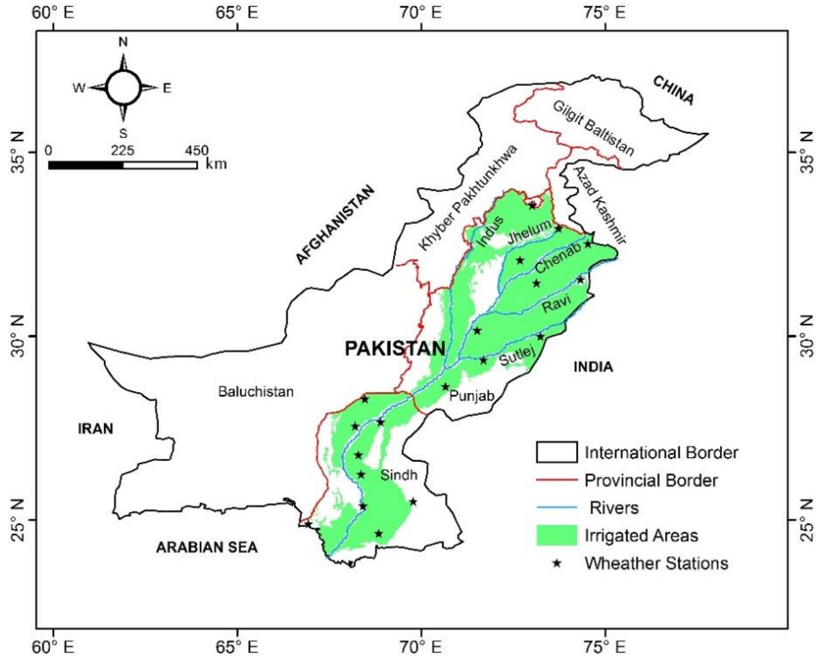

Figure 2.1 Map of the study area.

2.2.2 The SPARE:WATER model

The SPARE:WATER (Multsch et al., 2013) model is used to calculate the water footprint of crops and the entire region. SPARE:WATER follows the general concept of estimating the water footprint according to Hoekstra et al. (2011) and is based on the widely used FAO56 Guidelines for computing crop water requirements (Allen et al., 1998). The regional WF (WF_{area}, $km^3\ yr^{-1}$) is estimated by summing up the products of all crop productions ($t\ yr^{-1}$) multiplied by their crop water footprint (WF_{crop}; $m^3\ t^{-1}$). The WF_{crop} is calculated by adding the green, blue and grey WF components which are determined by dividing the water requirements ($m^3\ ha^{-1}$) by the crop yield ($t\ ha^{-1}$). The water requirements of these components are calculated according to the sources of water use, i.e., "green" water requirement is equal to the minimum of crop evapotranspiration (ET_c) or effective rainfall (P_{eff}), "blue" water requirement is the irrigation requirement (IRR) and the "grey" water requirement is estimated as the leaching requirement (LR).

$$\mathbf{WF_{crop}} = \underbrace{\frac{\mathbf{min(ET_c\,,P_{eff})}}{\mathbf{Y}}}_{\textbf{green WF}} + \underbrace{\frac{\mathbf{IRR}}{\mathbf{Y}}}_{\textbf{blue WF}} + \underbrace{\frac{\mathbf{LR}}{\mathbf{Y}}}_{\textbf{grey WF}} \tag{2.1}$$

where P_{eff}, IRR and LR are effective rainfall, irrigation requirement, and leaching requirement, respectively, in [$m^3\ ha^{-1}$] and Y is crop yield in [$t\ ha^{-1}$].

SPARE:WATER requires two kinds of data inputs. First, a set of spatial model input data is used to initialize and run the model on the selected spatial domain. Second, the model needs to be parameterized to simulate crop specific evapotranspiration rates.

2.2.3 Spatial model input data

The input data required by SPARE:WATER includes climatic data, crop data and irrigation data (Table 1). The input data is provided in grid maps to calculate the crop water requirements and footprints for each grid cell. For a comprehensive list of all input data and further model parameters needed see Multsch et al. (2013). The efficiencies of the irrigation systems are set according to the FAO as 60%, 75%, and 90% for surface, sprinkler, and drip irrigation, respectively (Brouwer et al., 1985). The grey WF is estimated considering a local groundwater quality dataset collected by IWASRI during 2010−2014. We used the ArcGIS Geostatistical Analyst extension to interpolate the 3,500 point data from well measurements by ordinary kriging using an exponential semi−variogram. As no information is available on the quality of surface water, we use the same gridded data derived from the groundwater well measurements.

As this step introduces some uncertainty in our study, we performed sensitivity analyses to check the effect of irrigation water quality on the grey WF by changing the water quality input data. We set the EC of irrigation water as ±10, ±20 and ±30% to examine the consequence for the grey WF. Further, we also investigated the sensitivity of the irrigation efficiency on the blue and grey WF by varying the efficiency of the irrigation system. It is evaluated by changing the values from 45% to 75% in an interval of 5%. We neglected higher potential irrigation efficiencies through drip irrigation as this kind of irrigation is currently hardly applied in Pakistan.

Table 2.1 Spatial model input data used in this study.

Dataset	Description	Years/Resolution	Data Sources
Climate	Rainfall, wind speed, min. and max. temperature, relative humidity, sunshine hours for 19 weather stations	1997–2016 Monthly	Pakistan Meteorological Department
Irrigated areas	Spatial location of areas	2010	International Water Management Institute (IWMI)
Crop data	Harvested area and crop production	1997–2016 Yearly	Pakistan Statistics Bureau Islamabad
Crop parameters	Sowing and harvesting date	–	National Agromet Centre of Pakistan
Groundwater quality	Electric conductivity dataset of 3500 wells	2010–2014	International Water−Logging and Salinity Research Institute (IWASRI)

2.2.4 Parameterization

The crop evapotranspiration is determined by multiplying the reference evapotranspiration (ET_0) with crop coefficient (K_c). The reference evapotranspiration is derived from the Penman−Monteith equation (Allen et al., 1998), which is based on climatic data (i.e., humidity, temperature, solar radiation, and wind speed). The K_c value is adjusted by dividing the crop development period into four stages as initial (L_{in}), development (L_{dev}), mid (L_{mid}) and late (L_{late}) stage. The length of the crop development stages is taken from information provided from the Nation Agromet Center of Pakistan. We use Kc values corrected for crop height presented by Ullah et al. (2001). Missing K_c values of some crops, i.e., vegetables, fruits and fodder crops, are taken from a FAO dataset for sub humid regions (see K_c values in Table S–2.1). We also obtained information on crop height from the same source to adjust the FAO Kc values for specific weather conditions as described by Multsch et al. (2017). The effective rainfall P_{eff} is estimated by deducting the runoff losses (RO) from net rainfall (P), which is derived as a constant ratio of 20% of rainfall (RO=P×0.2) (Allen et al., 1998). The irrigation requirement is estimated by combining the productive and unproductive portions of irrigation water. Productive irrigation water is calculated by subtracting the effective rainfall from crop evapotranspiration (ET_c). If the effective rainfall is larger than ET_c, no irrigation is needed and vice versa. The unproductive irrigation water is calculated based on the efficiency of the irrigation system by considering the additional volume of water that is lost due to deep percolation or direct surface evaporation. Off−farm water losses such as seepage and evaporation from irrigation channels are neglected. The leaching requirement in the SPARE:WATER is estimated according to the salinity tolerance limits of each crop as defined by Ayers and Westcot (1985) e.g. cotton >7.7 dS m^{-1} and wheat >6 dS m^{-1} have relatively high tolerance levels whereas sugarcane >1.7 dS m^{-1}, rice >3 dS m^{-1} and vegetables 1.0−2.5 dS m^{-1} have low salinity tolerance abilities.

2.2.5 Scenario evaluation

A number of straightforward scenarios (n = 37) are analyzed to derive optimal cropping sets in view of available water resources (Table S−2.2). Scenarios are defined on the basis of the SPARE:WATER results. The year 2016 is considered as a baseline with a harvested area of 18.35 million hectares (49% Rabi, 48% Kharif and 3% annual crops) and a WF_{area} of 174 km^3 (Figure S−2.1). As can be seen, most of the water is consumed during the Kharif season with 64% of the annual WF_{area}. Whereas, Rabi and annual crops require 30% and 6% of the WF_{area}, respectively. In the Kharif season, cash crops, i.e., sugarcane, cotton, and rice are dominating the WF_{area} by 85% (equal to 57% of the annual WF_{area}). Therefore, we developed multiple scenarios by substituting these three most water−intensive crops (with regard to their WF_{area}) in the form of a single crop replacement (or a set of two, and three crops with others) with other potential Kharif and annual crops (fruits), including other water demanding cash crops (i.e., sugarcane, cotton, and rice). We kept those water demanding crops in the scenarios to see potential effects of changes in irrigation efficiency on the total WF in different configurations of crop patterns. For the scenarios, we assume a constant total harvested area as given in the Baseline scenario year. For each scenario, the entire cropped area of one of the water−intensive crops is fully allocated to a single other crop (Table S−2.2). In SET1 (sc1–sc6), sugarcane is replaced six times by another crop. Similarly, in SET2 (sc7–sc12) and SET3 (sc13–sc18), cotton and rice crops are replaced with other potential crops respectively. SET4–6 are similar setups but consider two crops to be substituted at a time allocated to one other crop, i.e., sugarcane and cotton in SET4 (sc19–sc23), sugarcane and rice in SET5 (sc24–sc28) and cotton and rice in SET6 (sc29–sc33).

Finally, SET7 (sc34–sc37) includes a full replacement of all water−intensive crops, i.e., sugarcane, cotton, rice with other potential crops.

2.3 Results

2.3.1 Model plausibility

The results of SPARE:WATER are compared with literature data in two ways to test the plausibility of model. First, we contrast simulated ET_c by selecting specific grid cells from SPARE:WATER for which corresponding published information is available (Figure 2.2a–d). In a second approach, we compare our simulations of WF_{crop} with other simulations (Figure 2.2e).

A comprehensive dataset of crop evapotranspiration for 8 main crops at 37 sites across the Indus basin of Pakistan has been published by Ullah et al. (2001). Their results are in line with ours (R^2=0.93) (Figure 2.2a,b). The RMSE is also low (147 mm) indicating a very good match even for single crops. We conclude no structural deviation between the two assessments. Shakir et al. (2010) have estimated the crop evapotranspiration for 8 main crops at one site in the Indus basin (Figure 2.2a,c). These results are also in the same range as SPARE:WATER, again with a high R^2=0.97 and a low RMSE=100 mm. Part of both high correlations can be explained by similar approaches on how ET_c is estimated. Ullah et al. applied the FAO CROPWATER model that is based on the same FAO56 guideline that we used to estimate ET_c in our SPARE:WATER set up. Similarly, Shakir et al. calculated their ET_c values also on the principle of this guideline, and used – similar to SPARE:WATER – the same crop coefficients and lengths of growing seasons as presented by Ullah et al. Hence, the differences of ET_c are due to different simulation periods (SPARE:WATER 1997−2016; Ullah et al., 20−25 years average without information on years; Shakir et al. 1999−2006). The simulation study by Soomro et al. is also well aligned with the SPARE:WATER estimates given an R^2=0.89 and RMSE=139 mm (Figure 2.2a,d). They also followed the same FAO56 guidelines but estimated K_c values through a lysimetric approach and reported good agreement with the empirical values of Ullah et al. The correlation shows that ET_c of rice is partially lower, whereas in the case of Rabi fodder it is somewhat higher than the SPARE:WATER results. This can be explained by different lengths of the growing season in the model set ups for rice (SPARE:WATER, Ullah et al. and Shakir et al. 190 days; Soomro et al. 104 days) and for Rabi fodder (SPARE:WATER 180 days; Soomro et al. 208 days).

With regard to the WF_{crop}, the SPARE:WATER values highly correlate with results published by Ghufran et al. (2015). However, the 1:1 line in Figure 2.2e indicates that the two models systematically deviate from each other, as the WF_{crops} reported by Ghufran et al. are always lower. One reason is that Ghufran et al. have not considered the grey WF in their simulations. Further, it remains unclear how (and if at all) Ghufran et al. considered irrigation losses as there is no description on how they set this value in the CROPWAT model (version 8.0) they used. Finally, another reason why absolute values of WF_{crop} can differ is the scale of application. SPARE:WATER calculates site specific WF_{crop} whereas (Ghufran et al., 2015) have estimated the WF_{crop} at the national level. Disregarding the difference in absolute values, results are highly correlated with R^2=0.97 and RMSE 2785 m^3 t^{-1}. Overall the plausibility analysis shows that the SPARE:WATER results are comparable with literature data, both with regard to ET_c and WF_{crop}.

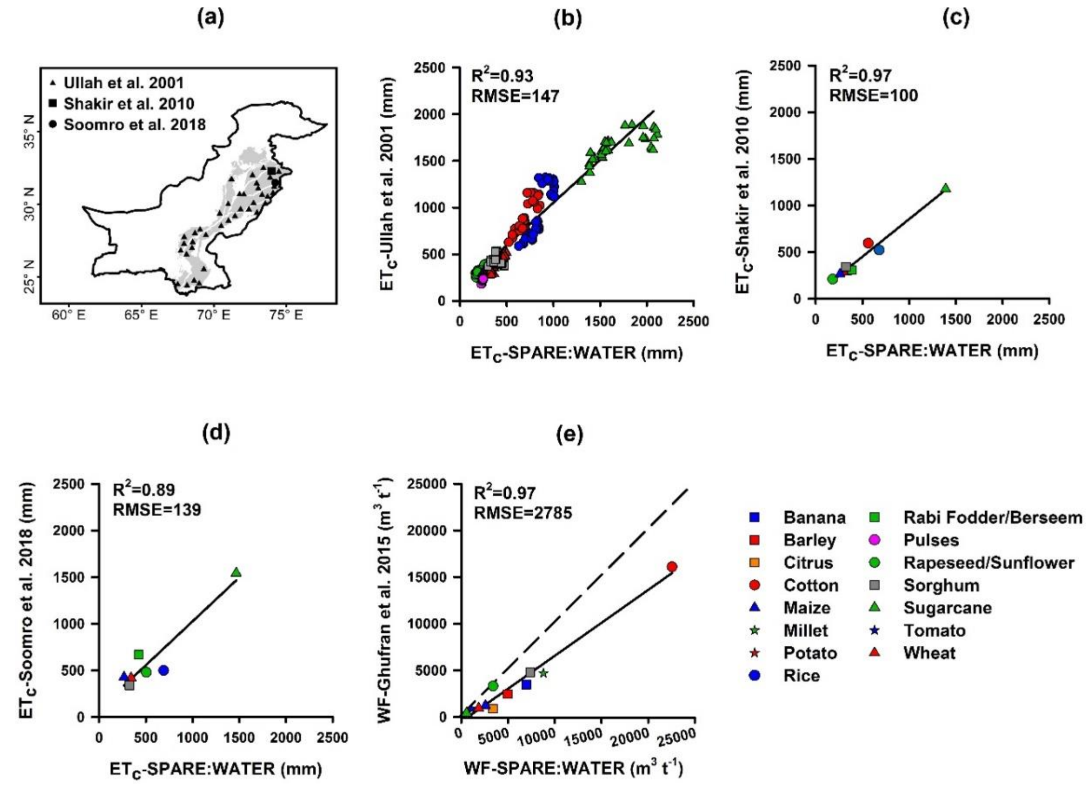

Figure 2.2 Comparison of SPARE:WATER with literature data: (**a**) location of data points used in model comparison; (**b**, **c**, **d**) correlations of simulated crop evapotranspiration (ET_c) with measured data; (**e**) correlation of simulated crop water footprints (WF_{crop}) with CROPWAT simulations.

2.3.2 Average water footprint of crops

The green, blue, grey and total WF of major crops are presented in Table 2 according to the cropping seasons. In the Kharif season, the highest value of WF_{crop} is estimated for cotton with 20690 m^3 t^{-1} because of the high IRR and a low crop yield of 0.53 t ha^{-1}. Other crops such as rice, millet, sesame and sorghum have a somewhat lower, but still relatively high WF_{crops} of 7001, 10240, 17423 and 8997 m^3 t^{-1}, respectively. At the lower end of our estimation are maize, fodder and vegetables crops (i.e., maize 2969 m^3 t^{-1}, fodder 875 m^3 t^{-1}, okra 1766 m^3 t^{-1}, gourd 1515 m^3 t^{-1}, onion 862 m^3 t^{-1} and tomato 1184 m^3 t^{-1}). Sugarcane has the lowest WF_{crop} in the Kharif season with 655 m^3 t^{-1}, but it has the highest IRR. This is due to the high biomass production of sugarcane with 50 t ha^{-1}.

In the Kharif season, the fractions of the blue WF_{crops} are 58%–78%, and thereby only slightly lower compared to the Rabi season. The green WF_{crop} of cotton, rice, maize, fodder, and miscellaneous crops are larger in the range of 21%–33%, whereas vegetables and sugarcane have low green WF_{crops} of 8% to 12%, respectively. The grey WF_{crop} of vegetables and sugarcane are higher in the Kharif season by 28% and 17%, respectively, whereas all other crops range between 3%–14%.

In the Rabi season, highest WF_{crops} are calculated for wheat and miscellaneous crops. The values for vegetables and fodder crops are at the lower range because of the high yields of these crops, with on average 13 and 31 t ha^{-1}, respectively. The fractions of the blue WF are in the range of 67%–85% and the green one of 6%–18%. The grey WF fractions are minor for most commodities except for vegetables (19–26%) and fodder (14%). In the case of annual crop (fruits), banana has the highest WF_{crop} with 7279 m^3 t^{-1} whereas the WF_{crops} of other fruits are moderate, ranging between 1822 and 3397 m^3 t^{-1}, respectively. The blue WF fractions are high in the case of all annual crops with 70%–78%, while green WF fractions are in the range of 12%–25%. The grey WF fraction is comparatively higher with 6–17%.

Table 2.2 Average yield and water footprint (WF) for crops in both cropping seasons in the Indus basin for the period 1997–2016.

Season	Category	Crops	Yield ($t\ ha^{-1}$)	WF ($m^3\ t^{-1}$)			
				Green	Blue	Grey	Total
Kharif	Cereal	Rice	2.1	1,488	4,971	542	7,001
		Maize	2.6	839	1,706	424	2,969
		Sorghum	0.7	2,981	5,763	253	8,997
		Millet	0.6	3,390	6,558	292	10,240
	Fiber	Cotton	0.53	6,886	13,315	489	20,690
	Sugar	Sugarcane	50	76	469	110	655
	Oilseed	Sesame	0.5	4,809	12,086	528	17,423
	Fodder	Sorghum(Jowar)	12.5	229	616	30	875
	Vegetables	Okra	8.3	109	1,387	270	1,766
		Gourd	8.7	104	1,186	225	1,515
		Onion	10.9	73	550	239	862
		Tomato	10.3	67	978	139	1,184
Rabi	Cereals	Wheat	2.7	381	2,083	100	2,564
		Barley	0.8	621	4,432	167	5,220
	Leguminous	Pulses	0.85	1020	6,320	964	8,308
	Oilseed	Rapeseed	0.95	750	3,151	192	4,093
	Spice	Pepper	1.7	387	4,451	1,246	6,084
	Tuber	Potato	13.8	56	733	180	969
	Fodder	Berseem	31	29	185	34	248
	Vegetables	Carrot	15.1	15	162	63	240
		Spinach	11.2	43	340	118	501
		Garlic	7.2	111	906	176	1,193
		Turnip	17.3	30	265	101	396
Annual	Fruits	Banana	4.3	945	5,704	630	7,279
		Citrus	8.7	416	2,391	590	3,397
		Dates	8.7	381	1,335	106	1,822
		Guava	12.2	299	1,791	353	2,443
		Mango	9.6	335	2,040	403	2,778

2.3.3 Regional water footprint for the period 1997–2016

Results of the estimation of the WF_{area} for 1997–2016 is depicted in Figure S–2.2a. There is a strong inter–annual variation with the lowest WF_{area} in 1997 (163 $km^3\ yr^{-1}$) and the highest in 2014 (201 $km^3\ yr^{-1}$). We find an overall negative trend of water productivity ($m^3\ t^{-1}$) and water consumption ($m^3\ ha^{-1}$) from 1997–2016 (Figure S–2.2b). The modified Mann–Kendall test revealed that the trend is significant for water productivity ($p = 0.01$), but not significant for water consumption ($p = 0.34$). The average WF_{area} is estimated to 182 $km^3\ yr^{-1}$, of which the blue WF_{area} component accounts for 75% (137 $km^3\ yr^{-1}$), followed by the green and grey WF_{area} of 17% (30 $km^3\ yr^{-1}$) and 8% (15 $km^3\ yr^{-1}$), respectively.

On a seasonal basis, the cropped area between the Rabi and Kharif remains stable while the share of commodities grown differ substantially (Figure 2.3a). The Rabi season is most important for wheat production (81% of the total area), which is the major food staple for the Pakistan people. Crop production is more diversified in the Kharif season with cotton, rice, fodder, and sugarcane sharing 33%, 30%, 12%, and 11% of the harvested area. On an annual basis, production of wheat requires the largest harvested area (39%) while cash crops (cotton, rice, sugarcane; note that rice is seen as a cash crop in Pakistan and all other crops are grown on 36% and 25% of the area, respectively. The Kharif crops have the largest share in the annual WF$_{\text{area}}$ with 64%, followed by Rabi crops (30%) and annual crops with 6% (Figure 2.3b). Consumption of water in the Rabi season is dominated by wheat which consumes 79% of the Rabi WF$_{\text{area}}$. Cash crops consume a large volume of water in the Kharif season with 28%, 30%, and 27% of the total. On an annual basis, the cash crops consume 57% of the WF$_{\text{area}}$, while wheat requires only 24% of the WF$_{\text{area}}$. The share of all other crops is 19% in the annual comparison. Note that the seasonal attribution of WF we show here depends on the allocation of single crops to crop groups. Sorghum, for example, is grown in the Kharif season as a cereal crop while it is also utilized as a fodder crop in the same season. Shakir et al. (2010) have not made this distinction and thus the cropping patterns they published deviate from ours.

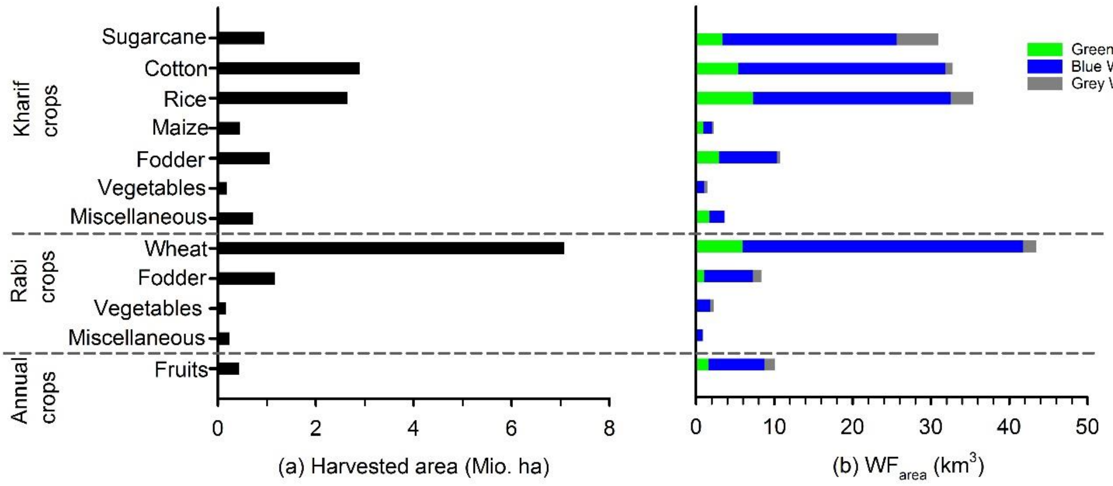

Figure 2.3 Average harvested area (**a**) and WF$_{\text{area}}$ (**b**) for the period 1997–2016.

2.3.4 Sensitivity analysis

A sensitivity analysis is performed similar to the one factor at a time methodology, i) to investigate the dependence of the grey WF_{area} by changing the salinity of the irrigation water, and ii) to examine the effect of irrigation efficiency on the blue and grey WF_{area}. The results indicate that the grey WF_{area} increased up to 52% when salinity, expressed as electric conductivity (EC) of irrigation water, increases by 30%. Similarly, the grey WF_{area} decreased up to 58% when the EC decreased by 30% (Figure 2.4a). However, as the grey WF_{area} only amounts to 8% of the total WF_{area}, the effect of accounting a potentially erroneous salinity of the irrigation water does not change the overall results of our study.

This is different for the second component of our sensitivity analysis. As we have assumed a field efficiency of the surface irrigation method of 60%, this efficiency was set as a reference. The result shows that the blue and grey WF_{area} increased substantially by up to 33% for an efficiency of 45%, and decreased by 20% when the field efficiency improved from 60% to 75% (Figure 2.4b). Related to the total WF_{area}, such a change would increase/decrease the total WF_{area} by +24/−19%.

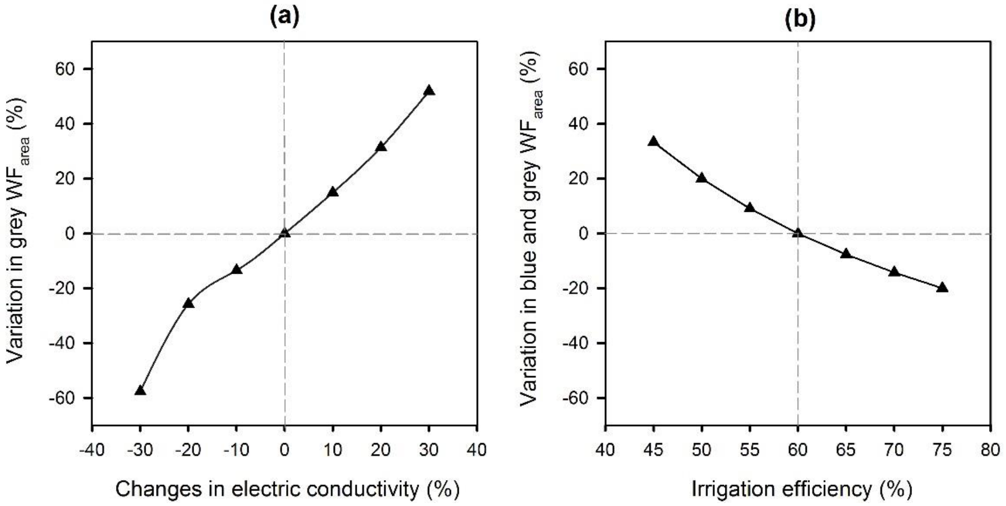

Figure 2.4 Sensitivity analysis of (**a**) electric conductivity and (**b**) irrigation efficiency and their effects on the grey and blue regional water footprints.

2.3.5 Scenario analysis

Cash crops are high water−intensive crops in the Kharif season, consuming 57% of the annual water (see baseline in Figure S−2.1). As an alternative, we established in total 37 scenarios by replacing each cash crop (or two/three cash crops) with a single other crop

(Table S–2.2, Figure 2.5a). Scenarios are grouped in sets according to the cash crop(s) replaced. As replacing crops, we considered all other Kharif crops including the cash crops and annual crops (i.e., sugarcane, cotton, rice, maize, fodder, vegetables, and fruits), but excluded miscellaneous crops. The changes in the WF_{area} for all scenarios are presented in Figure 2.5b. Figure 2.5c depicts an additional change of the irrigation efficiency and reduced salinities as outlined in the sensitivity analysis.

In SET1 (sc1–sc6), we substituted sugarcane which leads to a decrease in the WF_{area} of −4 to −16%. The largest decrease in sc3 is induced by increasing the cropped area of maize. SET2 (sc7–sc12) focused on replacing cotton, resulting in a diverse change of the WF_{area} with an increase of up to 30% (sc7) a reductions of up to −7% (sc9). The rice scenarios in SET3 (sc13–sc18) lead to increases of 29% (sc13) and 18% (sc18), and reductions of −5% to −12% for all other replacements. The fourth set of scenarios SET4 (sc19–sc23) considers the substitution of sugarcane and cotton with improvements in the WF_{area} of up to −23% (sc20) and a single combination with an increasing WF_{area} of 16% (sc23). SET5 (sc24–sc28) does not consider sugarcane and rice, achieving improvements of the WF_{area} by up to −28% (sc25) when growing maize and an increase when fruits are cultivated (sc28, +14%). The worst results are found for scenarios of SET6 (sc29–sc33) when sugarcane (+59%, sc29) and fruits (+39%, sc33) replace both, cotton and rice crops. Again, growing more maize leads to lowering the WF_{area} by −21% (sc30). Finally, in SET7 (sc34–sc37) sugarcane, cotton, rice are fully supplanted by maize, fodder, vegetables, and fruits, yielding reductions of −35%, −18%, −23% and an increase by 35%, respectively.

In all scenarios for which results are given in Figure 2.5b we assumed the traditional irrigation method (surface irrigation) as the current practice in Pakistan. To estimate the potential effect of improved irrigation technologies (i.e., application of drip irrigation for cotton, sugarcane, maize, vegetables and fruits whereas sprinkler for all other commodities) we re–run all scenarios (Figure 2.5c).

Water consumption of the current cropping pattern (baseline) can be reduced by −23% through improved irrigation. The overall highest WF_{area} reduction of −50% is found for sc34 by substituting sugarcane, cotton, and rice with maize, followed by sc25 (−44%, sugarcane, and rice substituted with maize), sc36 (−43%, sugarcane, cotton, and rice substituted with vegetables) and sc27 (−41%, sugarcane and rice substituted by vegetables). These results confirm that improved irrigation technologies have a very positive impact on water saving.

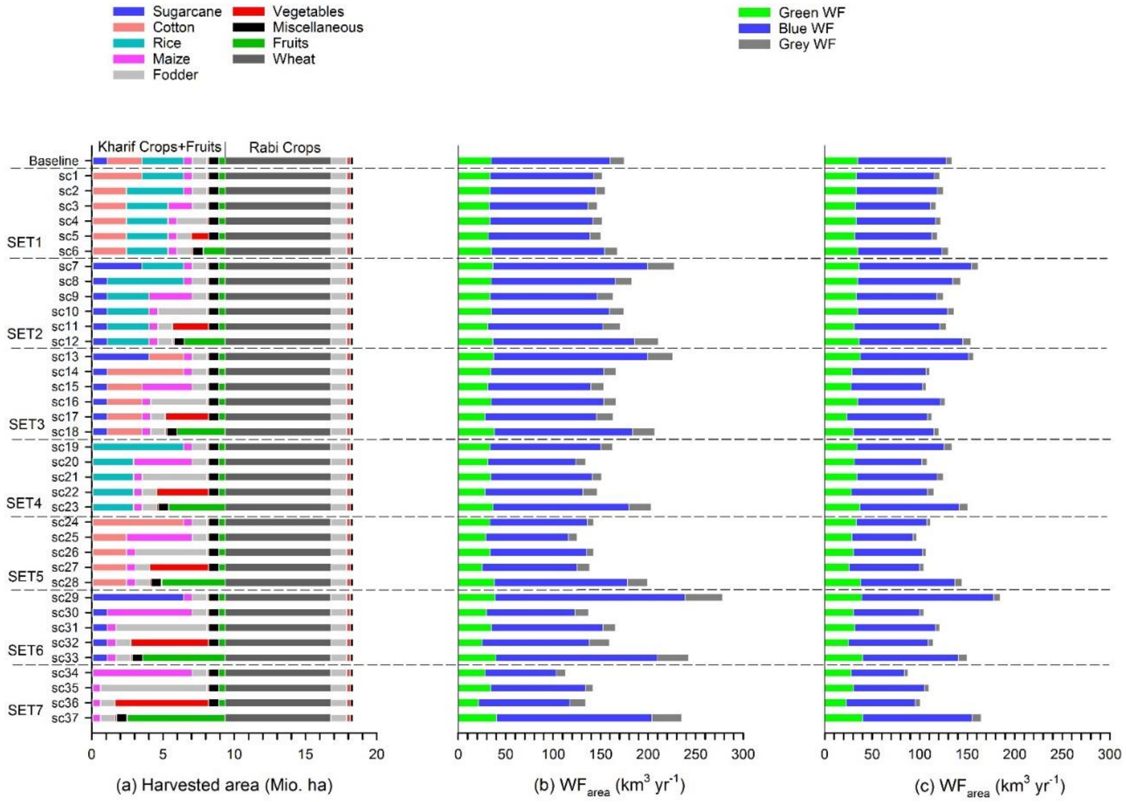

Figure 2.5 (**a**) Alternative cropping patterns; and (**b**) resulting WF$_{area}$; (**c**) WF$_{area}$ analysis of cropping pattern changes with concurrent changes in irrigation technologies.

2.4 Discussion

2.4.1. Water consumption and policy implication

In 2018, Pakistan's government has developed a water policy to ensure water and food security for the growing population. It specifies that future cropping patterns should be adjusted at the low delta crops through improved irrigation technologies. This policy has been established at the federal level as a national framework and it has been directed to provinces to make a master plan for the management of water resources. This study support the development of alternative water management strategies, through the evaluation of the water footprint. Numerous studies have suggested that a WF assessment can be a useful approach to evaluate management practices (Chukalla et al., 2015; Hess et al., 2010; Montesinos et al., 2011). It has been also discussed as a tool for policy implication in various regions. Spain's government has officially linked the WF analysis to decision making for new developing projects (Aldaya et al., 2010; Programmes, 2012). Liu et al. (2008) argued that current water policies of China are based on blue water consumption. However, it should be revised to take green water into account to further improve the water use efficiency. The potential of WF assessment as a performance indicator was also discussed by Dong et al. (2013) for policy implication in the Liaoning province of China.

Here we analysed the WF of Pakistan's agriculture to estimate the volume of water used during 1997–2016 to produce crops. Such type of analysis is useful to derive how much green versus blue water is needed for crop production (Chapagain et al., 2006). According to our estimates, the average water consumption in the study area is 182 km^3 yr^{-1}, of which 75% are allocated to blue water, 17% to green water and 8% to grey water, respectively. Sugarcane, cotton, and rice (cash crops) in Kharif and wheat in the Rabi season are the most commonly grown crops. Among them, sugarcane is the most water–intensive crop, followed by rice and cotton. These three crops are cultivated on 36% of the annual harvested area in the Kharif season, but consume about 57% of the annual WF_{area}. Wheat is cultivated as a food crop on 39% of the annual harvested area in the Rabi season. However, it consumes only 24% of the annual WF_{area}.

2.4.2 Alternative water management practices

In line with Pakistan's ambition to reduce water consumption, we analysed a number of simply water–saving strategies, i.e., by optimization of cropping patterns and through improvements of applied irrigation technologies. Adjusted cropping pattern allow to reduce the WF_{area} by up to −35% (sc34) through substituting the cash crops (i.e., sugarcane, cotton, and rice) with maize, while keeping the total cropped area constant. Apart from this ultimate scenario, sc1 (i.e., substitute sugarcane with cotton) and sc24 (i.e., substitute sugarcane and rice with cotton) are more balanced cropping patterns which reduce the water consumption by −13% and −18%, respectively. In light of these findings, we recommend to grow cotton in the harvested area of all cash crops if the absolute termination of all cash crops is not applicable. Various other studies conducted in different regions also indicate that the optimization of cropping patterns is a key approach to reduce the WF of a region or catchment (Aldaya et al., 2010; Dumont et al., 2013). Ghasemi et al. (2014) showed that the redistribution of cropping patterns can be linked to the effective use of water resources in Iran. Zeng et al. (2012) confirmed that the adjustment of cropping pattern is a key solution for water management of arid and semi−arid regions.

In the second part, we investigated the impact of optimal cropping patterns along with improvements of irrigation technologies. The results indicate that water consumption of the baseline cropping pattern (2016) can be reduced by up to −23 % through technological optimization alone. The WF_{area} of scenarios can even be decreased by up to −50% through the combined implementation of optimal cropping patterns and improved irrigation technologies. The technology changes lead to a decrease in water consumption for all cropping scenarios except for sc29 (i.e., cotton and rice replaced with sugarcane) as compared to the baseline cropping pattern at current irrigation settings. The benefits of improved irrigation have been also discussed in other studies. For examples, Maisiri et al. (2005) investigated the impact of irrigation technologies on maize and vegetable crops at an experimental site in the Limpopo basin of Zimbabwe, and Liu et al. (2013) found that less water was consumed when wheat was irrigated with sprinkler than surface irrigation in North China.

In Pakistan, most agricultural fields are irrigated with surface irrigation methods (Rizwan et al., 2018). Although various efforts have been made over the last three decades to introduce more efficient irrigation technologies, the results are not remarkable. The high initial cost is one of the main reasons for the adoption of these technologies. Rodrigues et al. (2012) studied the economic impacts of drip and sprinkler irrigation on maize crops in southern Brazil and concluded that the comparative advantages of water−saving are insufficient to recover the initial cost of the system. The Punjab government and World Bank have introduced a joint project (PIPIP, 2012−2021) on a subsidy basis to install high−efficiency irrigation systems on approximately 50,000 hectares in the Punjab province (PIPIP). Such types of projects can help to promote irrigation technologies among farmers by reducing the initial investment. Qamar et al. (2018) investigated the implementation strategies in the Punjab province for the sustainability of irrigation systems and recommended that water prices need to be sufficiently high to promote water−saving technologies among farmers. In another study, Kahlown et al. (2007) do not expect an adaptation of irrigation technologies in the Indus basin command areas due to the low price of water. However, further investigation should be conducted on water price formulation to encourage the farmers for improvements of irrigation technologies.

2.5 Conclusion

In this paper, we have evaluated a number of water−saving strategies in the irrigated areas of the Punjab and Sindh provinces in Pakistan. We have shown that substantial reductions in water consumption are possible through changes in cropping patterns. In the scenarios of changing cropping patterns, we substituted water−intensive cash crops (i.e., sugarcane, cotton, rice) with less water−intensive crops (i.e., maize, fodder, and vegetables) or replaced comparatively high water−intensive cash crops with less water−intensive cash crops. We further show that water savings are possible by shifting the irrigation method from surface irrigation to improved irrigation technologies (sprinkler and drip irrigation).

Additionally, socio−economic aspects may have an important role in the adoption of alternative management practices. Abdulai et al. (2011) showed that the household and farm characteristics such as age, education, income, loan accessibility, farm size, and location of the irrigation sources played a vital role in south Ghana for the selection of irrigation technologies and cropping patterns. Rehman et al. (2015) investigated the economic impact of major crops on the GDP of Pakistan and indicated that cotton, wheat, rice, and maize crops have a positive relationship with GDP while sugarcane crops have a negative effect. In another study, Mojtabavi et al. (2018) recognized that stopping the exports of agriculture commodities is not a wise decision for the economic perspective of a country, so net benefits of alternative cropping patterns should be close to the current benefits. Aldaya et al. (2010) highlighted that 'more crop per drop' investigation should also consider economic aspects to achieve 'more cash per drop' at the same time.

Apart from economic considerations, the impact of future climate changes in the Indus basin should also be considered. Rasul et al. have shown that these changes can reduce crop productivity and degrade the available water resources in upcoming years due to spatial and temporal changes in temperature and rainfall (Mahmood et al., 2012). Awan et al. (2016) predicted that climate changes will cause to rise the irrigation requirements by 7−11% in the region due to fluctuations in temperature and rainfall. Henceforth, we propose that joint social, economic and climate change impacts of alternative practices should be assessed in future studies to achieve sustainable development in water policy implications.

The current study is conducted to evaluate the water−saving strategies at the basin−level by choosing a random combination of crops. Future optimization strategies should include spatially adapted crop combinations, preferably in dependence of localized accessibility of groundwater and its quality. Multsch et al. (2017) have shown the value of such an optimization tool for the use of a limited water resource obtained from desalination in Saudi−Arabia. In addition, a similar type of a user−friendly decision support tool could be developed for field level application. Such a tool could provide farmers directly with information on optimal cropping patterns. We also recommend that apart from the proposed water−saving strategies, other alternative management techniques, directed to off−farm (i.e., improved infrastructure to reduce water losses due to poor conveyance efficiency) and on−farm (e.g., deficit irrigation or soil mulching) management, should be evaluated in future studies to develop a comprehensive water policy for Pakistan.

Supporting Information

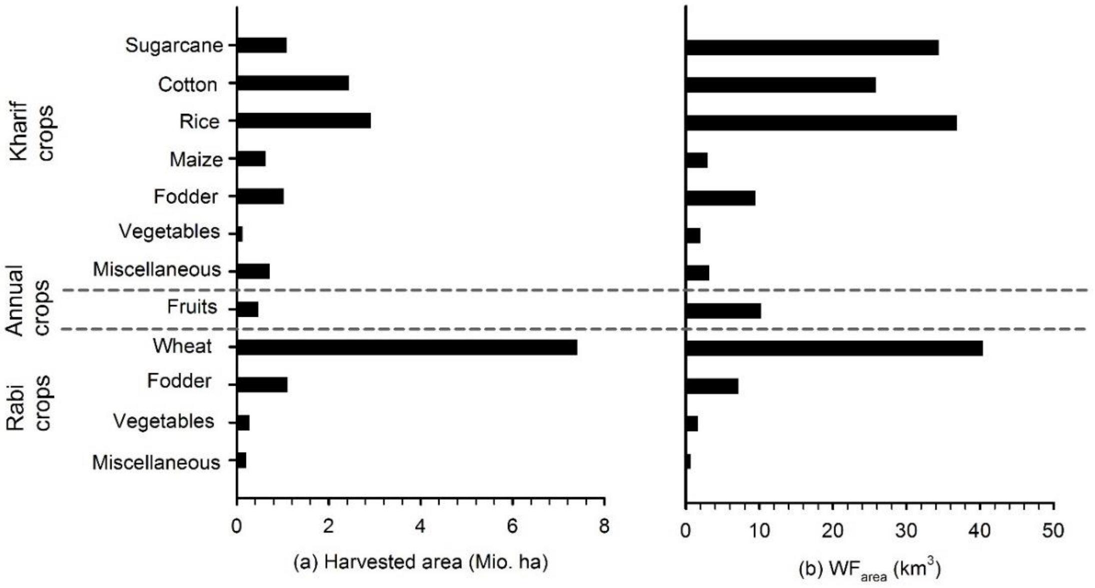

Figure S–2.1 (**a**) Harvested area; and (**b**) WF$_{area}$ of crop production for the baseline year 2016.

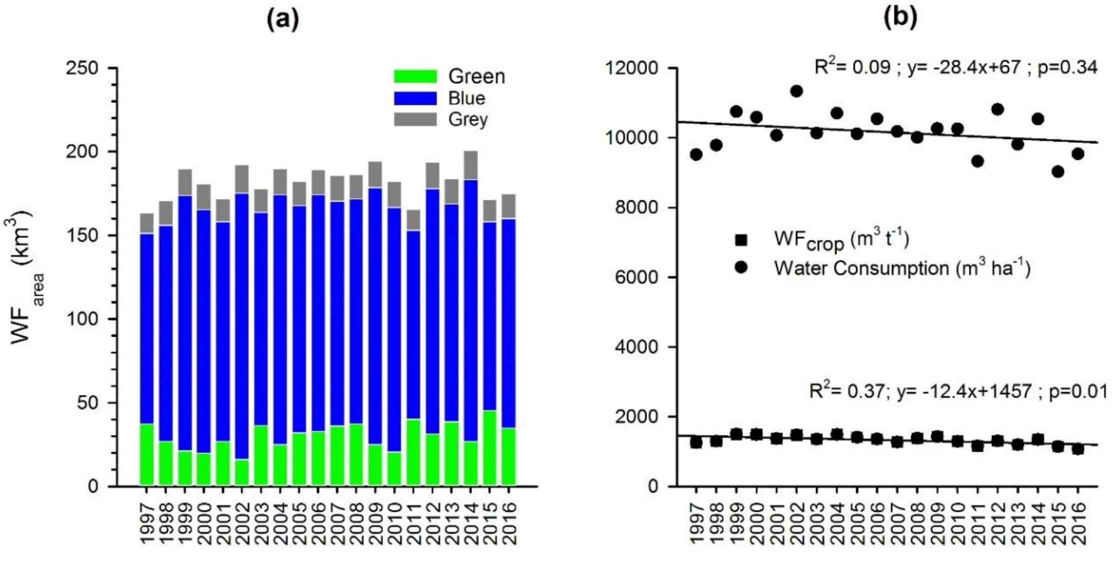

Figure S–2.2 Trends of (**a**) water footprint components; and (**b**) water productivity (m^3 t^{-1}); and water consumption (m^3 ha^{-1}) from 1997–2016.

Table S–2.1 Crop coefficients (Kc) used in this study.

Category	Crops	Crop Coefficients			Source
		$K_{c\,in}$	$K_{c\,mid}$	$K_{c\,end}$	
Cereal	Maize	0.15	0.82	0.47	Ullah et al. 2001
	Rice	0.28	1.26	0.44	
	Sorghum	0.23	0.92	0.52	
	Wheat	0.36	1.16	0.40	
Fiber	Cotton	0.44	1.11	0.38	
Sugar	Sugarcane	0.52	1.17	0.88	
Oilseed	Rapeseed	0.25	0.97	0.32	
Leguminous	Pulses	0.37	0.95	0.34	
Cereal	Barley	0.30	1.15	0.25	FAO Dataset
	Millet	0.30	1.00	0.30	
Vegetables	Carrot	0.70	1.05	0.95	
	Garlic	0.70	1.00	0.70	
	Gourd	0.50	1.00	0.80	
	Onion	0.70	1.05	0.75	
	Okra	0.70	1.05	0.95	
	Spinach	0.70	1.00	0.95	
	Tomato	0.60	1.15	0.70	
	Turnip	0.50	1.10	0.95	
Spice	Pepper	0.60	1.05	0.90	
Tuber	Potato	0.50	1.15	0.75	
Oilseed	Sesame	0.35	1.15	0.35	
Fodder	Berseem	0.40	0.90	0.85	
Fruits	Banana	1.00	1.20	1.10	
	Citrus	0.75	0.70	0.75	
	Dates	0.90	0.95	0.95	
	Mango	0.60	0.80	0.60	
	Guava	0.80	1.00	0.80	

Table S–2.2 Harvest area of the baseline year 2016 and the 37 cropping scenarios.

SET	Scenarios	Harvested Area (million hectares yr^{-1})											
		Kharif Season Crops							Annual Crops	Rabi Season Crops			
		Sugarcane	Cotton	Rice	Maize	Fodder	Vegetables	Miscellaneous	Fruits	Wheat	Fodder	Vegetables	Miscellaneous
	Baseline	1.09	2.43	2.92	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
SET1	sc1	0	3.52	2.92	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc2	0	2.43	4.01	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc3	0	2.43	2.92	1.71	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc4	0	2.43	2.92	0.62	2.12	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc5	0	2.43	2.92	0.62	1.02	1.22	0.71	0.46	7.41	1.10	0.27	0.20
	sc6	0	2.43	2.92	0.62	1.02	0.12	0.71	1.55	7.41	1.10	0.27	0.20
SET2	sc7	3.52	0	2.92	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc8	1.09	0	5.34	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc9	1.09	0	2.92	3.04	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc10	1.09	0	2.92	0.62	3.45	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc11	1.09	0	2.92	0.62	1.02	2.55	0.71	0.46	7.41	1.10	0.27	0.20
	sc12	1.09	0	2.92	0.62	1.02	0.12	0.71	2.88	7.41	1.10	0.27	0.20
SET3	sc13	4.01	2.43	0	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc14	1.09	5.34	0	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc15	1.09	2.43	0	3.53	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc16	1.09	2.43	0	0.62	3.94	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc17	1.09	2.43	0	0.62	1.02	3.04	0.71	0.46	7.41	1.10	0.27	0.20
	sc18	1.09	2.43	0	0.62	1.02	0.12	0.71	3.37	7.41	1.10	0.27	0.20
SET4	sc19	0	0	6.43	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc20	0	0	2.92	4.13	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc21	0	0	2.92	0.62	4.54	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc22	0	0	2.92	0.62	1.02	3.64	0.71	0.46	7.41	1.10	0.27	0.20
	sc23	0	0	2.92	0.62	1.02	0.12	0.71	3.98	7.41	1.10	0.27	0.20
SET5	sc24	0	6.43	0	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc25	0	2.43	0	4.63	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc26	0	2.43	0	0.62	5.03	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc27	0	2.43	0	0.62	1.02	4.13	0.71	0.46	7.41	1.10	0.27	0.20
	sc28	0	2.43	0	0.62	1.02	0.12	0.71	4.47	7.41	1.10	0.27	0.20

Table S–2.2 Cont.

		Harvested Area (million hectares yr^{-1})											
SET	**Scenarios**	**Kharif Season Crops**							**Annual Crops**	**Rabi Season Crops**			
SET6	sc29	6.43	0	0	0.62	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc30	1.09	0	0	5.96	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc31	1.09	0	0	0.62	6.37	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc32	1.09	0	0	0.62	1.02	5.47	0.71	0.46	7.41	1.10	0.27	0.20
	sc33	1.09	0	0	0.62	1.02	0.12	0.71	5.80	7.41	1.10	0.27	0.20
SET7	sc34	0	0	0	7.05	1.02	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc35	0	0	0	0.62	7.46	0.12	0.71	0.46	7.41	1.10	0.27	0.20
	sc36	0	0	0	0.62	1.02	6.56	0.71	0.46	7.41	1.10	0.27	0.20
	sc37	0	0	0	0.62	1.02	0.12	0.71	6.89	7.41	1.10	0.27	0.20

3 Climate Change Adaptation Strategies for Sustainable Water Management in the Indus basin of Pakistan

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3.1 Introduction

Pakistan's agriculture survives on irrigation as the environment of the Indus plain varies from arid to the semi–arid. Surface water originates from the Indus and is distributed to farmers through canals network on a supply basis (Muzammil et al., 2021). The Indus basin irrigation system is unable to cover the irrigation requirements of the territory leading to the use of groundwater for irrigation. A rising tendency of the harvested area is imposing further pressure on the water resources of Pakistan (Kirby et al., 2017). Farmers pump the groundwater to cover up to 60% of the surface water deficit. The water table is dropping to inaccessible depths owing to unsustainable pumping rates at the plain (Cheema et al., 2014). On top of the groundwater depletion, the irrigation water quality is deteriorating with high salinity (0.5–9.0 dS m^{-1}) in the Indus basin due to already saline stream water and high salinity of groundwater due to saline pockets that existing naturally in the aquifers. Saline irrigation water has increased soil salinity of irrigated areas by 23% in the Punjab and 78% in the Sindh province (Qureshi et al., 2008). Irrigation is applied to crops via inefficient irrigation methods, most often via surface irrigation that has an efficiency of below 50% (Kahlown et al., 2007; Mian et al., 2019).

Despite the already existing problems at the status quo, Pakistan's irrigation agriculture faces serious threats from future climate change impacts (Gul et al., 2022; Saddique et al., 2022). Many studies revealed that irrigated areas of Pakistan could be hotspots of climate change. This will affect irrigation requirements, partly because of changes in the length of the growing season, eventually leading to induced pressure on the already threatened water resources of Pakistan (Ahmad et al., 2020; Hussain et al., 2019; Z, 2021). Pakistan has a further big challenge to manage in view of food security due to its growing population (Kirby et al., 2017). Zhu et al. (2013) analyzed the impacts of climate change on both water resources and food production in Pakistan and reported that future water availability will either decrease or increase, depending on scenarios, but crop production and food security impacts are negative.

Various studies have proposed action plans and strategies to address water security in irrigation agriculture for optimal and more sustainable water resources management. For example, soil mulching to conserve soil moisture (Kader et al., 2019), conservation tillage to increase water use efficiency (Bekele et al., 2022), irrigation scheduling to avoid over–irrigation (Millán et al., 2020), as well as crop rotation and diversification to increase resilience under water stress condition (Nouri et al., 2019). Basharat et al. (2014) investigated the challenges and opportunities for sustainable water management in the Indus basin of Pakistan and recommended that more canal water should be allocated to areas with low water tables. Arshad et al. (2009) studied the impact of water losses through surface water supplies in the Indus basin of Pakistan and reported that up to 22% of water could be saved through lined watercourses.

Doulgeris et al. (2015) evaluated the deficit irrigation method to mitigate climate change impact in the Nestos River basin in Greece, and proposed that deficit irrigation secures more water for the downstream ecosystems. Myint et al. (2021) projected that alternative cropping strategies could be effective for sustainable water management and climate adaptation to improve future food security. Frisvold and Bai (2016) anticipated that improved irrigation technologies could achieve better control to adapt to climate change than traditional surface irrigation. Ghaffar et al. (2022) indicated that climate–resilient technologies and drought–resistant crops are ways to counteract the negative impacts of climate change in terms of water availability. Meanwhile, the government of Pakistan is looking forward to reducing the burden on water resources caused by increasing food demand and climate change. As an action plan, the government has proposed a national water policy that promotes growing low delta crops in the summer (Kharif season). Together with the use of improved irrigation technologies instead of status quo surface irrigation methods, this has a major contribution to agricultural water consumption (National Water Policy, 2018). Low delta crops are crops of high water use efficiency, of which maize is the best alternative compared to high water–intensive crops which are often grown as cash crops, i.e., sugarcane, cotton, and rice.

However, even by switching within different high delta crops, an enormous amount of water can be saved (Ahmed et al., 2021; Muzammil et al., 2020). Hence, the novelty of this study is that it considers various impacts and scenarios on future water use in Pakistan. The study focuses not only on substituting high delta crops with generally less water−intensive crops but also on replacing the status quo irrigation method (surface irrigation) with improved irrigation technologies under various climate change impacts. Further, the harvested area of crops is projected to estimate the real impact of crop production on water consumption. Finally, we it is taken into account that that climate change will affect the vegetation period of crops.

The water requirements of crops are estimated according to the sources of water use. For example, green water (GWU) is the amount of water that comes from precipitation and feeds the soil water storage. Blue water (BWU) originates from surface water and groundwater providing water resources for irrigation. Grey water (GrWU) is the volume of water that is required to washout the salts from the root zone to combat salinization. These three water sources reflect the common terminology of the water footprint accounting scheme and are estimated using the SPARE:WATER (Multsch et al., 2013) tool that is based on the widely accepted FAO Cropwat model for crop water requirement estimation (https://www.fao.org/land−water/databases−and−software/cropwat/en/). Further, a regression method is used to project the future harvested area in the Indus basin of Pakistan. Finally, the mechanisms of climate change on crop growth and the resulting crop water requirements using projections of the Coupled Model Intercomparison Project (CMIP5) are estimated. In this study, two Representative Concentration Pathways (RCP) are selected, i.e., the minimum and maximum emission scenarios RCP2.6 and RCP8.5, respectively, to determine the lower and upper bound estimates of future water demand in the medium (2031−2060) and long term (2061−2090). The objectives of this study are to i) estimate the future agricultural water consumption considering trends of harvested area and climate change impacts on the vegetation period, ii) investigate the impacts of alternative cropping patterns and improved irrigation methods as water saving strategies. It should be noted that the water−saving strategies are evaluated without considering changes in yield potentials and socioeconomic aspects that may have a significant impact in the adaptation of these policies. It is recommend that future studies should not only include water sovereignty, but also food sovereignty. The latter includes the consideration of food demand and the nutritional value of produced crops, as well as locally adapted combinations of crop rotations and arable crops.

3.2 Materials and methods

The study focuses on investigating climate change adaptation strategies for sustainable water management in the Indus basin of Pakistan. The first step is to estimate the water consumption of the entire region under current conditions as a baseline scenario and for future crop production under climate change impacts. In the next step, the impacts of alternative water management strategies are investigated. The methodological steps of the current study are given in Figure 3.1, while details of the study area and calculation methods are given in the following sections.

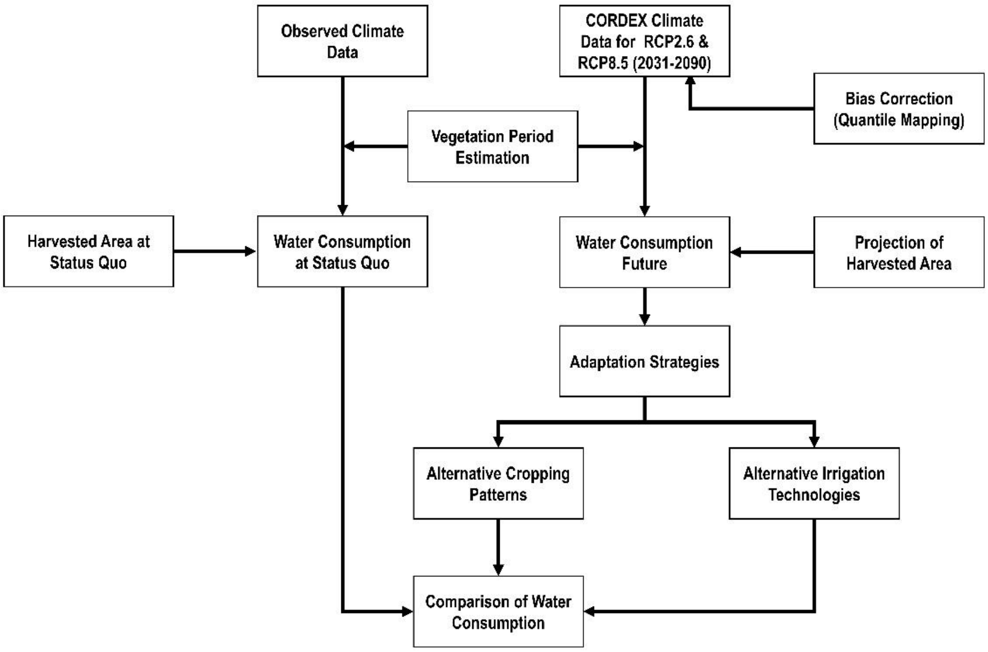

Figure 3.1 Methodological steps of the current study.

3.2.1 Study area

The study focuses on the 17 million hectares irrigated plains of the Punjab and Sindh provinces (Figure 3.2), where climate varies from arid to semi–arid with significant spatial and temporal variability in rainfall and temperature. The average annual rainfall is 390 mm, of which 80% occurs during summer. The summer season extends from April to September (max. temperature 34–44°C) and the winter season from December to February (max. temperature

20–28°C). Crops are harvested in two cropping seasons called Kharif (April–September) and Rabi (October–March). Cotton, rice, and sugarcane are leading crops in the Kharif and wheat is the prominent crop in the Rabi season. The Indus basin irrigation system is used to supply irrigation water. It consists of a network of channels that link the rivers to watercourses via canals. Groundwater is also used up to 50% as a supplementary source to compensate for the deficit in water supply. Water is applied to crops almost entirely via surface irrigation with an efficiency of up to 60%.

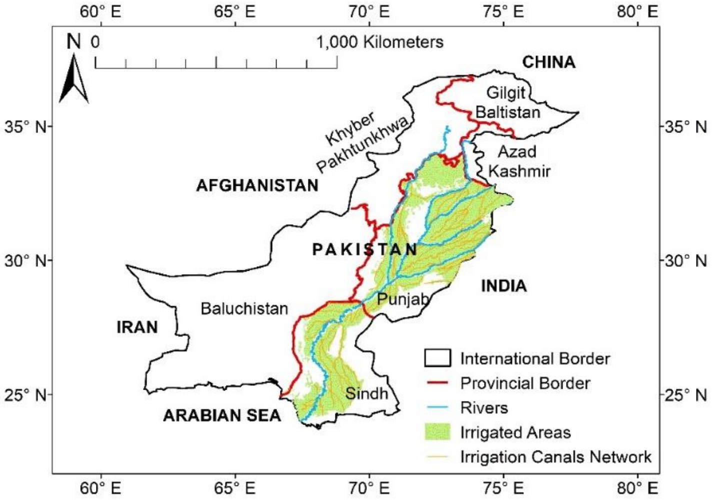

Figure 3.2 Map of the study area.

3.2.2 Climate data

The monthly climate data (1977–2006) including precipitation, temperature, wind speed, relative humidity, and sunshine hours are taken from the Pakistan Metrological Department. Further, a future climate dataset is used from the Coordinated Regional Climate Downscaling Experiment (CORDEX) for South Asia having a spatial resolution of 0.22° (~25 km × 25 km). From CORDEX data, regional climate model (RCM) outputs are used from dynamically downscaled General Circulation Models (GCM) conducted under the Coupled Model Inter–comparison Project Phase 5 (CMIP5). In this study, three RCMs [COSMO–Cr (CLMcom–ETH.MPI.M–ESM–LR), REMO2015 (GERICS.MOHC–HadGEMZ–ES), RegCM4 (ORNL.NCC–NorESM1–M)] are evaluated, which cover all necessary data to compute the crop water requirements. Further, the quantile mapping (QM) technique is applied for bias correction of RCM dataset. Studies show that it is one suitable method for bias correction of the CORDEX data (Enayati et al., 2020; Pasten–Zapata et al., 2020).

In the next step, Taylor diagrams are used to analyze the RCM outputs in a comparative assessment (Taylor, 2001). Taylor diagrams are commonly evaluated to measure the degree of correspondence between modeled and observed values (Ahmed et al., 2020; Arshad et al., 2021; Ko et al., 2019). The diagram summarizes three statistical measures, i.e., the root mean square error (RMSE), the standard deviation (SD), and the Pearson correlation coefficient. The reference evapotranspiration ET^{o} of all three RCMs at six agrometeorological stations are compared with reference data (2008–2020) to select the most well–performing RCM. Based on the RCM's performance, the REMO2015 is selected in the study for further analyses of RCP2.6 and RCP8.5. The selection criteria of RCM are given in appendix A1.

3.2.3 Estimation of the vegetation period

Numerous studies reveal that ambient temperature is a key driver in crop phenology (Bhattacharya, 2022; Kawakita et al., 2020; Tariq et al., 2021). In this research, the Growing Degree Day (GDD) concept (Eq3.1) is followed that is widely used in phenology to relate crop growth with changes in temperature. This approach is considered appropriate to determine the vegetation period as affected by climate change when crops could mature earlier due to an increase in temperature. The vegetation period is estimated to accumulate the GDDs. A crop matures when the seasonal accumulated GDDs reach a required GDD level (Kukal and Irmak, 2018). The GDD concept has been applied in various other studies for the same crops considered in this work, i.e., sugarcane (Ahmad et al., 2016), maize (Abbas et al., 2017), cotton (Saifullah et al., 2022), wheat (Banihashemi et al., 2021; Shaheen et al., 2020), and rice (Mishra et al., 2013). GDDs are calculated as follows.

$$\boldsymbol{GDD = \frac{(T_{max}+T_{min})}{2} - T_{base}} \qquad \text{(Eq3.1)}$$

where T_{max}, T_{min}, and T_{base} are the maximum, minimum, and base temperatures respectively. Crop development occurs when the average temperature remains above the base temperature. A plant does not grow at or below T_{base}, thus GDDs remain zero (Zhou and Wang, 2018). T_{base} values and required cumulative GDDs of major crops are taken from the Pakistan Agriculture Research Council (PARC), which are given in Table S–3.1.

3.2.4 Estimations of irrigation requirements

In this study, the SPARE:WATER (Multsch et al., 2013) model is used to estimate the water consumption in crop production, which has been used in various large scale application on the management of water resources. Examples include Saudi Arabia (Multsch et al., 2017), Brazil (Multsch et al., 2020), the Nile Basin (Multsch et al., 2017), the Murray–Darling River Basin (Multsch et al., 2014) and the Ogallala Aquifer (Multsch et al., 2016). Muzammil et al. (2020) validated the SPARE:WATER to calculate the water consumption in the Indus basin of Pakistan and investigated alternative water saving techniques. SPARE:WATER calculates the crop water requirement (CWR) by combining the GWU, BWU, and GrWU components. These components are calculated according to the sources of water use (Eq3.2), i.e., GWU is equal to the effective precipitation (P_{eff}), BWU indicates the irrigation requirement (IRR), and GrWU specifies the leaching requirement (LR).

$$\boldsymbol{CWR = min(ET_c, P_{eff}) + IRR + LR} \qquad \text{(Eq3.2)}$$

Where ET_c, P_{eff}, IRR, and LR are given in m^3 ha^{-1}. The regional water consumption (CWR_{area}; km^3 yr^{-1}) is determined by adding the CWR of each crop (m^3 ha^{-1}). SPARE:WATER requires spatial input data to run the model and needs a parameterization to calculate the crop evapotranspiration. The crop evapotranspiration (ET_c) is estimated from the crop water balance model by multiplying the reference evapotranspiration (ET°) with a crop coefficient (K_c). ET° is calculated from the Penman–Monteith equation by using monthly climate data, i.e., minimum and maximum temperatures, relative humidity, sunshine hours, rainfall, and wind speed (Allen et al., 1998). K_c values are taken from published data and are separated according to the length of four growing stages, i.e., initial, development, mid, and late (Muzammil et al., 2020). P_{eff} is calculated by subtracting the runoff losses from the aggregated rainfall (Allen et al., 1998).

IRR is estimated by considering the productive and unproductive water use in crop production (Eq3.3). The productive irrigation water is an amount of water that contributes to crop growth. The unproductive irrigation water is an extra amount of water to cover the water losses from evaporation and deep percolation and it is calculated by considering the efficiency of the irrigation system (η_{irr}). Irrigation efficiencies are selected according to the FAO guidelines as 90%, 75%, and 60% for drip, sprinkler, and surface irrigation, respectively (Brouwer et al., 1985).

$$\boldsymbol{IRR} = \frac{\boldsymbol{IRR_{Prod}}}{\eta_{\boldsymbol{irr}}} \qquad \text{(Eq3.3)}$$

The leaching requirements are calculated according to the salinity of irrigation water and allow salt tolerance limits for each crop as described by FAO (Ayers and Westcot, 1985); cotton for example has a higher tolerance (7.7 dS m^{-1}) than vegetables (1.0–2.5 dS m^{-1}). Point data of groundwater quality are taken from the International Waterlogging & Salinity Research Institute (IWASRI) and interpolated by using the kriging technique. In this study, it is assumed that the water quality of surface water and groundwater is the same at status quo conditions and in the climate change scenarios. Muzammil et al. (2020) show in a sensitivity analysis with the same dataset used here that the effects of different salt concentrations influence GrWU, but that this only plays a minor role in the overall water use.

3.2.5 Projection of harvested area and water Use

The historical trend of crop production (1947–2020) is used to project the future harvested area in the territory. A regression method is applied to a spatial dataset of major crops (cotton, wheat, sugarcane, rice, maize) taken from the Pakistan Statistic Bureau (PBS). In this paper, it is assumed that the harvested area of minor crops will remain the same compared to the status quo. Further, it is kept in mind in the regression analysis that the maximum allowable land for agriculture is set by the Pakistan Statistic Bureau.

3.2.6 Water management and cropping pattern strategies

Muzammil et al. (2020) evaluate a number of straightforward cropping scenarios to derive optimal cropping patterns for the Indus basin of Pakistan. The study reveals that sugarcane, cotton, and rice are the most water–intensive crops. Muzammil et al. (2020) recommend three most favorable cropping scenarios of which sugarcane, cotton, and rice replaced with maize (SC3) is the ultimate cropping scenario followed by substitution of sugarcane with cotton (SC1) and sugarcane and rice with cotton (SC2). In this study, the impacts of these three recommended cropping scenarios are investigated in line with future climate change. In addition, the impact of improved irrigation technologies on water saving will be investigated in order to determine these effects also in the status quo and for the climate change scenarios.

3.3 Results

3.3.1 Projection of vegetation period and harvested area

An increase in ambient temperatures shortens the length of the vegetation period according to the GDD concept due to an earlier crop emergence, an earlier maturity and a reduced number of days between both. The future projection of changes in the vegetation period is shown against the baseline (Figure 3.3). The vegetation period in the 2030s decreases by 6–16 and 8–18 days under RCP2.6 and RCP8.5, respectively. The strongest reduction of the vegetation period is found for rice (RCP2.6: reduction of 16 days; RCP8.5: 18 days) and a short reduction is observed for sugarcane (RCP2.6: 6 days; RCP8.5: 9 days). The vegetation period in the 2060s decreases by 4–15 days in RCP2.6 and 5–23 days in RCP8.5. The largest decrease is estimated for maize in RCP2.6 (18 days) and wheat in RCP8.5 (23 days) while a lower reduction in the vegetation period is observed for sugarcane (RCP2.6; 5 days) and cotton (RCP8.5; 14 days).

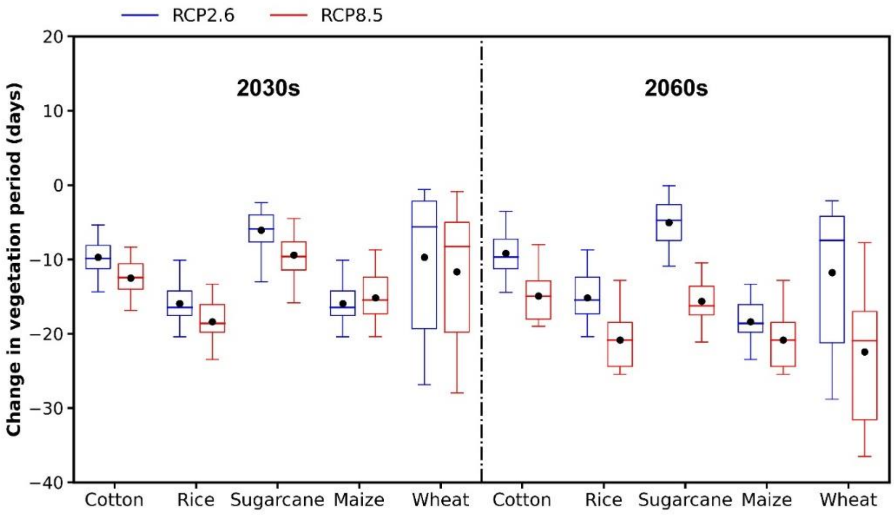

Figure 3.3 Climate change impacts on the vegetation period of the four dominant crops grown in the Kharif season of the Indus basin of Pakistan.

Figure 3.4 shows the harvested area of major crops (1947–2020) and linear projections up to 2090. Wheat is the leading crop in the study area followed by cotton, rice, sugarcane, and maize. Since 1947, the harvested areas of all crops are increasing continuously apart from cotton where a decline in trend is observed near 2010. Results indicate that the largest increase in future harvested area compared to the status quo is found for wheat (4.8 Mha), followed by cotton (2.2 Mha), rice (1.8 Mha), sugarcane (0.5 Mha), and maize (0.3 Mha).

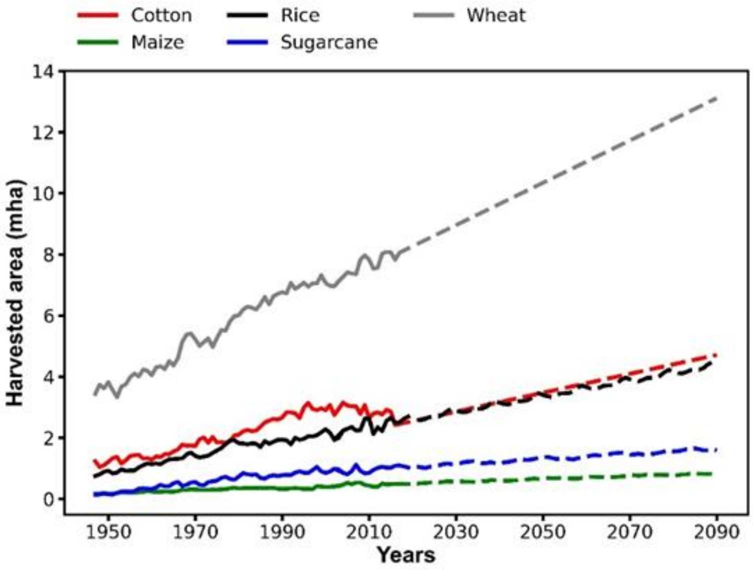

Figure 3.4 Projection of harvested area in the Indus basin of Pakistan (1947−2090).

3.3.2 Projection of temperature and precipitation

Since bias−corrected data of RCM REMO2015 is selected in this study on a performance basis, the threshold values of temperature and precipitation (before and after bias correction) are presented in the appendix Tables A2 and A3. The historical and future trends of precipitation and temperature under climate scenarios RCP2.6 and RCP8.5 are depicted in Figure 3.5. It can be seen that the precipitation trends are increasing for the historical (R^2=0.013, p=0.45) and the RCP2.6 scenario (R^2=0.006, p=0.37) and decreasing for the RCP8.5 scenario (R^2=0.005, p=0.70). However, Mann−Kandall tests reveal that the trends are not significant for all scenarios. For temperature, the historical trend is increasing with a mean temperature increase of 0.4−0.5°C. Further, the future trends are also increasing for both scenarios, with mean temperatures (2030−2090) of 0.5−2.0°C for RCP2.6 and 1.1−4.3 for RCP8.5. The Mann−Kandall test show that the trends are significantly increasing for the historical (R^2=0.28, p=0.0005), RCP2.6 (R^2=0.44, p=8.14x10^{-08}) and RCP8.5 (R^2=0.80, p=2.62x10^{-14}) scenarios.

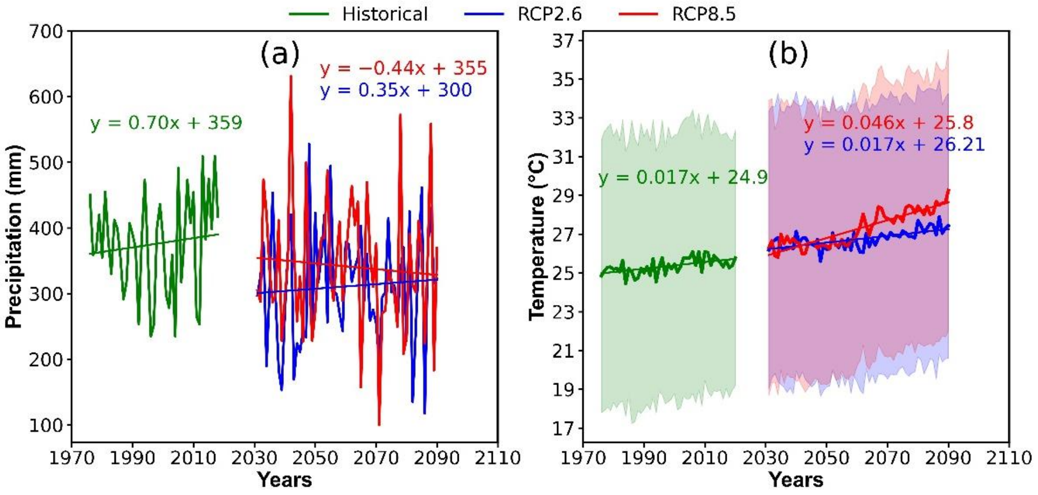

Figure 3.5 Historical (1977−2020) and future (2031−2090) trends of (**a**) precipitation; and (**b**) temperature (shaded areas depict the minimum and maximum temperature).

3.3.3 Regional water consumption (CWR_{area})

The regional water consumption (CWR_{area}) for the historical (1997−2020) and future (2031−2090) projection under climate scenarios (RCP2.6 and RCP8.5) are estimated for no changes in harvested area and linear projection of harvested area by considering the status quo irrigation settings and alternative improved irrigation technologies (Figure 3.6). Results show that the average CWR_{area} for the baseline period (1997−2020) is estimated to 184 km^3 yr^{-1}, of which BWU accounts for 76% (139 km^3 yr^{-1}) followed by GWU 16% (29 km^3 yr^{-1}) and GrWU 8% (16 km^3 yr^{-1}) (Figure 3.6a). The Mann−Kendall test indicates that the water consumption trend is negative, but not significant (p=0.30).

In the first step, the future CWR_{area} is projected under status quo irrigation settings (surface irrigation) with an irrigation efficiency of about 60% (Brouwer et al., 1985). Results with no change in the irrigation area indicate that the average CWR_{area} under RCP2.6 increases by 10% (2030s) and 11% (2060s) (Figure 3.6b). BWU increases by 12% (2030s) and 13% (2060s). A similar increase is found for RCP8.5 with 11% in the 2030s and 7% in the 2060s, and BWU increases by 12% and 8% in the 2030s and 2060s, respectively (Figure 3.6c). Meanwhile, GWU increases slightly in both scenarios and GrWU remains stable. The results of projected harvested area show that average CWR_{area} increases by 50% in the 2030s and 73% in the 2060s under RCP2.6 (Figure 3.6d), with an even stronger increase for the BWU by 62% (2030s) and 83% (2060s). Similarly, the average CWR_{area} in RCP8.5 increases by 49% and 68% in the 2030s and the 2060s (Figure 3.6e), respectively, and the BWU rises by 60% in the 2030s, and 79% in the 2060s. In both climate scenarios (RCP2.6 and RCP8.5), a slightly higher GWU is observed due to increased precipitation, while changes in GrWU remain marginal.

In the second step, the future CWR$_{area}$ is estimated to replace the status quo irrigation settings with improved irrigation technologies (drip and sprinkler). Irrigation efficiencies are assumed to be 90% and 75% for drip and sprinkler irrigation, respectively (Brouwer et al., 1985). Improving irrigation efficiency leads to an extreme reduction in water demand. With no change in harvested area, the average CWR$_{area}$ decreases by 15% in the 2030s and 16% in the 2060s under RCP2.6 (Figure 3.6b). BWU decrease at the same time by 14% in the 2030s and 15% in the 2060s. The average CWR$_{area}$ in the RCP8.5 scenario (Figure 3.6c) decreases by 16% (2030s) and 18% (2060s) and the BWU by 15% (2030s) and 17% (2060s).

For projected harvested area under RCP2.6, the average CWR$_{area}$ increases by only 11% and 29% in the 2030s and the 2060s (Figure 3.6d), respectively, and even the sharp increase of BWU is more than halved with +20% (2030s) and +35% (2060s). Similar increments are found for the CWR$_{area}$ under RCP8.5 with +10% in the 2030s and +23% in the 2060s under RCP8.5 (Figure 3.6e). The BWU also increases following improvements in irrigation technology, but substantially less than compared to the status quo conditions with 18% in the 2030s and 23% in the 2060s. Similar to status quo irrigation settings, the changes in GWU and GrWU are very marginal.

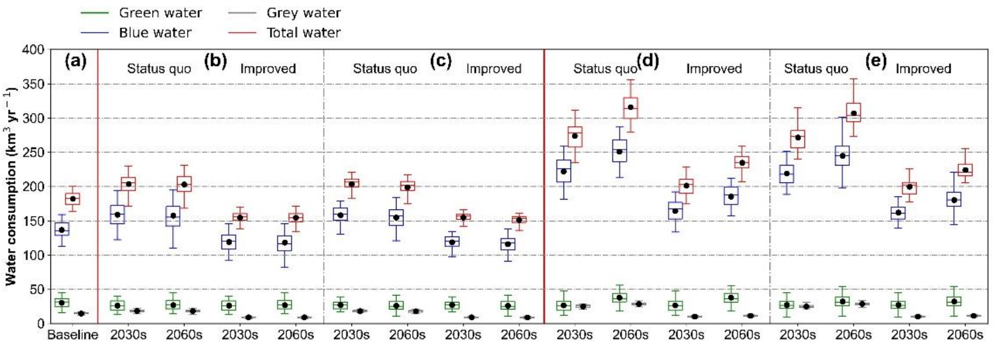

Figure 3.6 Regional water consumption (CWR$_{area}$) with status quo irrigation settings and improved irrigation technologies for the (a) baseline, no changes in the irrigation area for (b) RCP2.6 and (c) RCP8.5, and with irrigation area projection for (d) RCP2.6, and (e) RCP8.5 scenarios.

3.3.4 Impact of alternative cropping scenarios

Muzammil et al. (2020) show that cash crops (i.e., sugarcane, rice, and cotton) are highly water−intensive and consume 57% of the current total water consumption in the Indus basin. Among the cash crops, cotton consumes less water and maize is the least water−demanding crop. Hitherto, three alternative cropping scenarios SC1 (cotton replaced to sugarcane), SC2 (cotton replaced to rice & sugarcane), and SC3 (maize replaced to cotton, rice & sugarcane) are developed to compare future CWR_{area} for projected harvested area with the baseline conditions (2020) at status quo and alternative improved irrigation settings. In order to see whether a change in cropping patterns provides an alternative pathway for agricultural land use in the future in view of limited water resources availability. The harvested areas of crop for baseline and scenarios are given in Table S−2.2 (*chapter 2*).

Figures 3.7a−c depict the impacts of alternative cropping patterns on CWR_{area} at status quo irrigation settings for the current baseline year 2020 and climate change scenarios RCP2.6 and RCP8.5, respectively. Where SC1 leads to substituting sugarcane with cotton, the average CWR_{area} increases by 43% (2030s) and 67% (2060s) at RCP2.6 conditions compared to the baseline, mainly dominated by rising shares of BWU with 56% in the 2030s and 76% in the 2060s. In RCP8.5, the average CWR_{area} increases marginally less by 42% (2030s) and 61% (2060s) compared to the baseline, and the surplus for BWUs are similar with 54% in the 2030s and 73% in the 2060s. SC2 focuses on replacing sugarcane and rice with cotton, which reduces the projected increases of the CWR_{area} substantially by 29% (2030s) and 46% (2060s) in RCP2.6 compared to the baseline. Reductions of the BWU are not as strong and around 10% less for the 2030s and 2060s compared to SC1. Again, slightly less reduced water demands are found for RCP8.5, with an expansion of the CWR_{area} by 27% and 41% in the 2030s and 2060s, and enlargements of the BWUs by 38% (2030s) and 52% (2060s). Finally, SC3 considers all water−intensive crops, i.e., sugarcane, rice, and cotton to be replaced with maize. Here the largest water savings are found. The average CWR_{area} for the RCP2.6 scenario even decreases by 1% in the 2030s and increases by 14% in the 2060s compared to the baseline. In RCP8.5, CWR_{area} reduces by 3% in the 2030s and it raises by 8% in the 2060s. Changes are mainly due to increases of the BWU in the same range in the mid (2030s) and long term (2060s). Note that in all scenarios, the contribution of GWU remains stable for SC1 and SC2 but that it reduces marginally for SC3 due to the shorter vegetation period of maize. The contribution of GrWU is generally low for all scenarios, w0ith a noteworthy variation small surplus in SC1 compared to SC2 and SC3, respectively.

The impact of alternative cropping patterns at improved irrigation technologies is investigated to study the collective effect on water saving (Figure 3.7d,e). As can be seen when comparing Figure 3.5 changing cropping patterns together with improving irrigation is very effective. For SC1 (sugarcane replaced with cotton), the average CWR_{area} in RCP2.6 increases by 1% and 14% in the 2030s and 2060s, respectively, compared to the baseline year, mainly triggered by the BWU, which increases by 6% and 18% in the 2030s and 2060s, respectively. In RCP8.5, the average CWR_{area} even reduces by up to −2% in the 2030s and −11% in the 2060s compared to the baseline. This reduction is recorded even though the BWU increases in this scenario by up to 8% in the 2030s and 18% in the 2060s. SC2 (sugarcane and rice replaced with cotton) reduces the average CWR_{area} in RCP2.6 by −8% in the 2030s and increases by 7% in the 2060s compared to the baseline. In this case, the BWU is reduced by −1% in the 2030s and increases by +11% in the 2060s. For RCP8.5, the average CWR_{area} decreases by up to −9% in the 2030s while it increases by up to 2% in the 2060s compared to the baseline, and for the BWU a decrease by up to 3% in the 2030s and an increases by 8% in the 2060s is recorded. SC3 (sugarcane, rice, and cotton replace with maize) provokes a decline in the average CWR_{area} in RCP2.6 compared to the baseline year 2020 by up to −16% and −2% in the 2030s and 2060s, respectively. The BWU decreases similarly by −15% and −5% in the 2030s and 2060s. The overall strongest decrease of CWR_{area} is found for the RCP8.5 scenario, as it goes down by up to −19% (2030s) and −6% (2060s) compared to the baseline, accompanied by reductions in the BWU of −19% and −9% in the 2030s and 2060s, respectively. Absolute changes in GWU and GrWU are marginal for all scenarios. However, relative decreases are strong for GrWU by −35% for SC1 and SC3 as well as −60% for SC3 compared to the baseline.

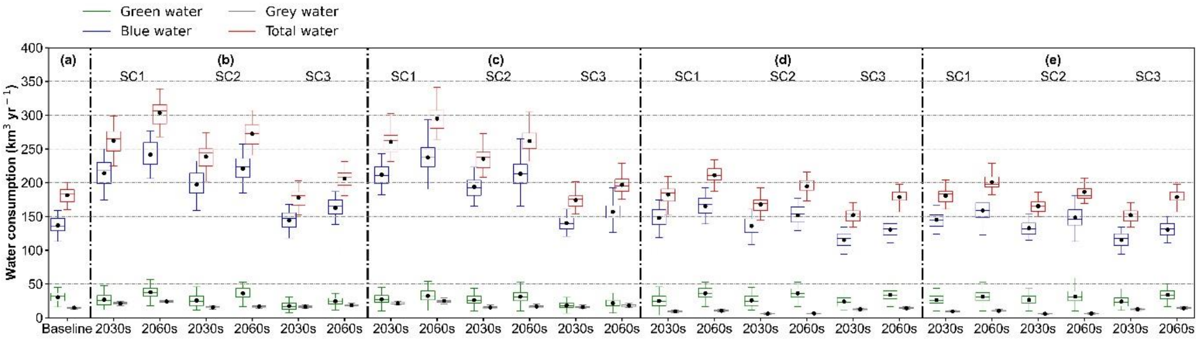

Figure 3.7 Regional water consumption (CWRarea) (a) in the baseline year 2020 and (b) alternative cropping scenarios SC1 (cotton replaced by sugarcane), SC2 (cotton replaced by sugarcane and rice), and SC3 (maize replaced by cotton, sugarcane, and rice) with status quo irrigation settings under climate scenario RCP2.6, and (c) RCP8.5. Similarly, the same SC1 (cotton replaced by sugarcane), SC2 (cotton replaced by sugarcane and rice), and SC3 (maize replaced by cotton, sugarcane, and rice) scenarios under climate scenarios assuming improved irrigation technologies for (d) RCP2.6, and (e) RCP8.5.

3.4 Discussion

3.4.1 Future's water consumption

Pakistan is situated in one of the global hotspots where climate change impacts could be the worst. Raja et al. (2018) revealed that Pakistan ranks as the 7th most vulnerable countries to climate change in the world. The World Bank reported that hotspots are primarily predicted in Pakistan where Sindh could be the most susceptible followed by the Punjab province (Mani et al., 2018). Since irrigation requirements depend mainly on hydro–metrological conditions, climate change could impact crop water requirements (Du et al., 2021; Khelifa et al., 2021). The impact of climate change on future CWR_{area} is analyzed under the climate scenarios RCP2.6 and RCP8.5. The estimates show that the average CWR_{area} (1997–2020) under the status quo conditions is 184 km^3 yr^{-1}. BWU contributes around 76% to the total water demand, followed by GWU with 17% and GrWU by 8%. In the climate scenarios (RCP2.6 & RCP8.5), the average CWR_{area} increases up to 50% in the 2030s and up to 73% in the 2060s owing to the collective impact of climate change and a projected increase in the harvested area. Despite the overall worse consequences of RCP8.5, the average CWR_{area} is estimated up to 5% higher in the RCP2.6 than RCP8.5 due to the impact of the length of the vegetation period that is projected to reduce stronger in RCP8.5 compared to RCP2.6. This results in a 4% higher BWU for RCP2.6, whereas GWU and GrWU are estimated up to 31% and 3% lower compared to RCP8.5, respectively. Various studies anticipated that future irrigation requirements could decrease when climate warming reduces the crop's vegetation period. Xiao et al. (2020) studied the climate change impact on the water use of wheat and maize in the north China plain and showed that a warmer climate might lead to a decrease in water consumption owing to the shortening of the growth period. Deihimfard et al. (2022) calculated the future water footprint of wheat in Iran and indicate that the water footprint declines due to an increase in crop yield and a decrease in water consumption. Lovelli et al. (2010) investigated the effects of increasing atmospheric carbon dioxide concentrations on crop evapotranspiration in the Mediterranean and concluded that a reduction in the vegetation period does not compensate for the increasing effect on evapotranspiration demand. Supit et al. (2010) showed that the crop water requirements of wheat in Europe is decreasing due to the shortening of the growing season as a result of rising temperatures. Banihashemi et al. (2021) studied the impact of climate change on growth indices of wheat, barley, and maize for future periods in Qazvin Plain Iran. Their results showed that water use efficiency, crop yield and biomass will increase up to 20–40% in the future. Another study showed that irrigation requirements for wheat decreases by 5% in Zimbabwe, caused by a reduction in the growing degree days (Govere et al., 2020).

3.4.2 Future's water management strategies

Pakistan is facing further future water resources depletion, where the growing population and climate change are serious threats to water security related to food security. Several studies have proposed various strategies and action plans to cope with water scarcity of the country. For example, cultivating drought–resistant crops (Rahimi–Moghaddam et al., 2021), deficit irrigation to exploit the water productivity (Pérez–López et al., 2018; Rodríguez Pleguezuelo et al., 2018), conservation tillage and mulching to preserve soil moisture (Jia et al., 2019) have been recommended to meet future challenges. A national–level policy has been implicated in Pakistan in 2018 as an action plan to ensure food security and climate change adaptation (National Water Policy, 2018). The policy proposes that Pakistan's future cropping patterns should consist of less water–intensive crops and that irrigation methods have to be improved through an increased use of drip and sprinkler irrigation. A similar type of initiative is being taken by the Indian government to grow less water–intensive crops in those areas where groundwater depletion is very high (Sharma, 2016). In this study, the impact of low delta crops and improved irrigation technologies is investigated in line with future climate change by following the national policy guidelines. Changes in atmospheric CO_2

concentrations and their potential impact on biomass production or yield have not been considered in the analysis. Despite the potential positive effects of increasing CO_2 concentrations on crop productivity, there are several negative effects, including increased respiration rates and increased incidence of pests, diseases and weeds (Malhi et al., 2021). Instead of using a crop model–based estimate of yields which would be needed to account for these diverse and intermingled effects, statistical data on crop production are used, as most studies on water footprint accounting do.

Our results reveal that low delta crops can reduce the gap between baseline and future CWR_{area} if the status quo cropping patterns are abandoned. Doing so, the ultimate scenario SC3 (sugarcane, cotton, and rice crops replaced with maize) restrains the change in the average CWR_{area} by −1% (2030s) to +14% (2060s) compared to the baseline. Meanwhile, SC2 (i.e., substitute sugarcane and rice with cotton) and SC1 (i.e., substitute sugarcane with cotton) are more balanced cropping patterns followed by SC3. Various studies also reveal that cropping pattern optimization is a key approach for effective water resources management (Boazar et al., 2020; Chouchane et al., 2020; Singh, 2018). (Multsch et al., 2017) investigated the impact of various cropping patterns on water demand in Saudi Arabia and propose that fodder crops should be replaced with vegetables or cereal crops for a more sustainable water use. Cui (2020) studied climate change adaptation in the USA and recommend that crop acreage adjustment have a significant impact on sustainable water use despite it being largely overlooked. Wang et al. (2017) proposed that growing drought–resistant crops in water–stressed areas is a promising strategy in response to future climate.

Further, the impact of improved irrigation technologies is investigated on the status quo and alternative cropping patterns. The result directs that the average CWR_{area} will increase up to 29% compared to the baseline if the status quo cropping pattern and irrigation methods remain. However, the average CWR_{area} even decrease up to −19% compared to the baseline by associating the alternative cropping pattern (SC3) and improved irrigation technologies. Other studies also show that technological changes lead to a decrease in water consumption and have the potential to mitigate climate change impact. For example, Malhi et al. (2021) specified that irrigation technologies reduce irrigation requirements and increase the resilience of crop production to climate change. Hamududu and Ngoma (2020) studied water resources availability in Zambia and propose that efficient irrigation technologies are highly recommended in the region for better water management to mitigate water stress. Pressurized irrigation systems and appropriate irrigation scheduling can increase water productivity in water scarce regions under the impact of climate change (Nikolaou et al., 2020). In Pakistan, water managers have made many efforts to encourage farmers towards the installation of improved irrigation technologies. However, high initial costs are one of the constraints in implementation. (Muzammil et al., 2021) depict that improved irrigation technologies are comparatively more expensive in Pakistan than surface irrigation methods, but solar−powered irrigation technologies are the most viable and cost−effective long term solutions among the available future options. Rodrigues et al. (2012) investigated the economic impact of drip irrigation on maize in Brazil and conclude that its cost−to−benefit ratio is high compared to surface irrigation. Recently, the government of Pakistan has introduced the subsidizing Punjab Irrigated−Agriculture Productivity Improvement Project (PIPIP) for farmers with the help of the World Bank for the implication of improved irrigation technologies. Studies show that such types of packages encourage farmers to adopt alternative technologies (Minkoff−Zern, 2014; Rizov et al., 2013).

3.5 Conclusion

Various water−saving strategies are evaluated for future sustainable water use in Pakistan in line with climate change. The findings show that water consumption will increase in the future as a linear trend due to the conjoint impact of increasing harvested area due to demographic change and climate change. The findings indicate that the climate scenario RCP2.6 could be more vulnerable than RCP8.5 due to slightly higher water consumption because of shorter vegetation periods in the latter scenario. However, cropping scenarios can largely reduce water consumption by replacing high delta crops (i.e., sugarcane, cotton, rice) with less water−intensive crops (i.e., maize). Further, a substitutional decrease in water consumption is also possible through the implementation of improved irrigation technologies. However, this analysis here represents an upper limit of the maximum savings possibilities.

Supporting Information

A Taylor diagram (Figure S–3.1) is constructed to see how well the reference evapotranspiration data of RCMs agrees with the observed data. In this analysis, it is assessed the data of six agrometeorological stations to study the comparative assessment of three RCMs. Further, RCMs are applied with and without bias correction. The diagram is drawn by plotting the three statistics parameters: 1) the root mean square error (RMSE) represents the distance from the point to the x–axis, 2) the standard deviation (SD) derives from the radial distance from the origin, and 3) the Pearson correlation coefficient (R) is proportional to the azimuthal angle.

Retrieved results of REMO2015 show that the R–value varies from 0.82–0.88 before bias correction and 0.94–0.96 after bias correction (Figure S–3.1). RMSE values ranges between 27–49 mm/month for uncorrected and 14–27 mm/month for corrected data. For COSMO–CR, R–values is slightly lower with 0.79–0.83 for uncorrected and 0.91–0.96 for corrected data. The RMSE varies between 31–52 mm/month before correction and 18–35 mm/month after correction. In the case of RegCM4, R–values range from 0.71–0.83 for uncorrected data and 0.89–0.95 for the corrected dataset. Here, RMSE is between 40–78 mm/month before bias correction and 26–53 mm/month after the bias correction. The overall results indicate that among all RCMs, the REMO2015 is very near to observed data for both cases, i.e., before and after bias correction. Hence it is decided to use the bias corrected REMO2015 for all further scenario analysis.

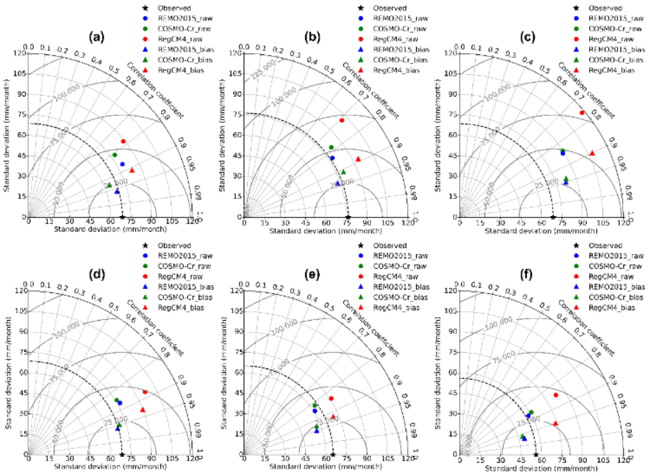

Figure S–3.1 Taylor diagram to relate statistical characteristics of simulated reference evapotranspiration ET° using three RCMs with (*_bias*) and without (*_raw*) bias correction and observed ET°.

Table S–3.1 Base temperature (T_{base}) and required cumulative growing degree–days (GDDs) of major crops.

Crops	Tb (°C)	GDDs
Cotton	12	2300
Maize	8	1750
Rice	10	2200
Sugarcane	9	4650
Wheat	5	1800

Table S–3.2 Threshold values of maximum and minimum temperature (Tmax, Tmin) before and after bias correction.

	Temperature	E_μ (°C)	E_SD (°C)	RMSE (°C)	R
Before Bias Correction	T_{max}	−2.30	1.11	5.08	0.86
	T_{min}	−2.52	1.08	5.17	0.83
After Bias Correction	T_{max}	−0.08	0.01	2.11	0.97
	T_{min}	−0.11	0.05	2.07	0.96

4 Economic and Environmental Impact Assessment of Sustainable Future Irrigation Practices in the Indus basin of Pakistan

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4.1 Introduction

Agriculture of Pakistan is based on irrigation where rainfall marginally meets 15% of crop water requirements (Qureshi et al., 2010). Irrigated agriculture is associated with the Indus basin, which provides irrigation water on a supply basis. Surface water resources are unable to fulfill the actual irrigation demands owing to the high evapotranspiration and salinity environment in the plain (Basharat et al., 2014). Groundwater covers 40−60% of the irrigation needs to meet the deficit in surface water supplies (Cheema et al., 2014). The intensive groundwater use results in a decline of the water table and accumulation of soil salinity, which originates from saline pockets of the aquifers (Qureshi et al., 2008). Meanwhile, the increasing trend of groundwater pumping has become energy exhaustive. It reduces the farmer's income because of high irrigation costs and leads to massive greenhouse gas releases, mainly CO_2 emissions, through energy consumption (Qureshi, 2014). Furthermore, the role of groundwater depletion in greenhouse emissions is still unaccounted, which can be a significant emission source associated with bicarbonate extraction (Mishra et al., 2018; Wood and Hyndman, 2017). Despite the poor situation of water resources availability in the country, inefficient irrigation methods dominate in the region, with losses of up to 50% of available water in the fields (Rizwan et al., 2018b).

In many arid and semi−arid countries, where water resources are limited and depleting rapidly, there is pressure to reduce water consumption for the water security of the growing population (Kahlown et al., 2007). Various management approaches have been suggested to save water, including deficit irrigation, soil mulching, conservation tillage, cultivation of drought resistance or low water demanding crops (Muzammil et al., 2020). Previous studies indicate that improved irrigation technologies (IIT) enable farmers to cope with water scarcity and insecure water supply (Muzammil et al., 2020; Wang et al., 2017; Zhang et al., 2019).

However, the impact of IIT remains a critical topic for sustainable irrigation. The consequences of IIT vary among regions because of differences in cost–benefits, off–farm environmental impacts, and social preferences (Wichelns and Oster, 2006). Economic impact assessment should be part of the evaluation process and support the decision–making. It can be used to project the levels of economic activity generated in a region by a specific project or alternatively without that project (Großmann et al., 2016). For example, Zou et al.(2013) analyzed water–saving strategies based on the climate change response for China and proposed that channel lining is a preferable strategy from an economic perspective compared to pressurized irrigation practices. Mahinda et al.(2016) investigated the economic impact of sorghum production via drip irrigation in semi–arid regions of Tanzania and recommended that two irrigations per day are beneficial to get higher economic returns. Narayanamoorthy et al.(2018) studied the economic impact of drip irrigation on vegetable crops and their findings indicate that the pressurized irrigation system offers high net returns compared to conventional irrigation methods.

However, irrigation development can also have severe environmental effects at regional and basin levels (Dogaru et al., 2019; FAO, 1997; Velasco–Muñoz et al., 2019). For example, Pandey (2013) studied the environmental impact of canal irrigation in India and concluded that construction of canal is beneficial to enhance the crop production, but it resulted in waterlogging and rising salinity. Daccache et al.(2014) projected that a pressurized irrigation system is capable to increase irrigation efficiency, but CO_2 emissions increase due to additional energy consumption compared to a gravity–fed surface irrigation system. Shekhar et al.(2020) showed that technology changes could have the potential to mitigate groundwater depletion through pressure reduction on water resources. However, the lower percolation from fields with improved water saving irrigation techniques may reduce aquifer recharge (Johnson et al., 1999).Mojid and Mainuddin (2021) revealed that high–efficiency irrigation technologies reduce agriculture water consumption, but large–scale adoption can lead to negative impacts on groundwater dynamics and the regional water cycle because of lower percolation rates to recharge the groundwater. Farsi aliabadi et al. (2020) investigated the environmental impacts of IIT supported by subsidized energy supply in Iran and found that such programs are not likely to overcome groundwater depletion. In Pakistan, the potential of IIT related to water saving have been recognized. Several studies revealed that it is possible to overcome water scarcity in Pakistan through the adoption of high–efficiency irrigation systems (Latif et al., 2016; Rizwan et al., 2018b; Zafar et al., 2020). Meanwhile, previous studies show that future power supply for IIT should consider changes in the energy source, including solar power supply (Hassan and Kamran, 2018; Mongat et al., 2015). Nevertheless, the economic and environmental impacts of these technologies are still unknown over the status–quo irrigation settings. An inclusive analysis of the cost–effectiveness of IIT coping with ecological impact can support economic development and environmental sustainability in the region.

In this study, we compare the economic and environmental impacts of the status–quo irrigation settings with alternative IIT. We use a coupled economic–environmental–modeling framework to estimate the irrigation costs, groundwater depletion, and CO_2 emissions to understand the return on investment and environmental effects. We consider improved, more sustainable irrigation technologies that differ from the status–quo irrigation practices in terms of water consumption, irrigation costs, and energy use. As the water consumption via IIT is lower than that of conventional irrigation, the effect of groundwater recharge through surplus irrigation is diminishing, which we take also into account. Furthermore, improving the established irrigation system needs a high initial investment and, in the case where the gravity–fed irrigation system is replaced, additional operational energy costs and associated CO_2 emissions come into play, which are also analyzed.

The objectives of the current study are: (1) to investigate the economic impact of IIT over status–quo irrigation practices, (2) to compare groundwater depletion and CO_2 emissions of the status–quo irrigation settings with improved irrigation practices, and (3) to develop alternative scenarios for IIT and identify sustainable energy use options in the irrigation agriculture of Pakistan.

4.1.1 Description of the study area

The study focuses on the irrigated areas of Punjab and Sindh provinces in the Indus basin of Pakistan. Together, these cover 17 million ha (Figure 4.1), representing 90% of the total irrigated area in the country. The topography of the plain falls from north to south, ranging from 540 to 4 m above mean sea level. The basin has an arid to semi–arid climate with complex hydrological processes due to spatial and temporal variation in the rainfall, temperature, land use, and water consumption. The average annual rainfall amounts to 379 mm (2002–2018), while maximum temperature ranges from 34–44°C in the summer (Apr–Sep) and 20–28°C in the winter (Dec–Feb). The annual potential evapotranspiration varies from 1,200 to 2,050 mm from the north to the south. Crops are harvested in two cropping seasons called Kharif (wet season; Apr–Sep) and Rabi (dry season; Oct–Mar). Sugarcane, cotton, and rice are dominant crops in the Kharif while wheat is a major crop in the Rabi season.

There are five major tributaries to the Indus (Indus, Chenab, Ravi, Jhelum, and Sutlej), which supply irrigation water via a network of canals and watercourses. The provincial governments distribute the surface water among farmers according to the landholding size and collect the water charges two times in a year in the Kharif and Rabi seasons. The water charges vary from province to province, i.e., the Punjab government collects at a flat rate despite which crop is grown while it varies in Sindh by crop to crop. Farmers use additional groundwater recourses via private units (tubewells), operate with diesel engines or mains power for groundwater pumping. The government provides subsidized electricity to farmers. However, diesel operated tubewells are common among farmers with 87% of share because they have a lower initial investment than electric operated tubewells. Crops are widely irrigated via surface irrigation with an application efficiency of 45–60%. Improved irrigation systems (drip and sprinkler) are installed only in a limited area (50,000 ha) through a subsidized program of the World Bank and the government of Punjab in the frame of the Punjab Irrigated–Agriculture Productivity Improvement Project (PIPIP).

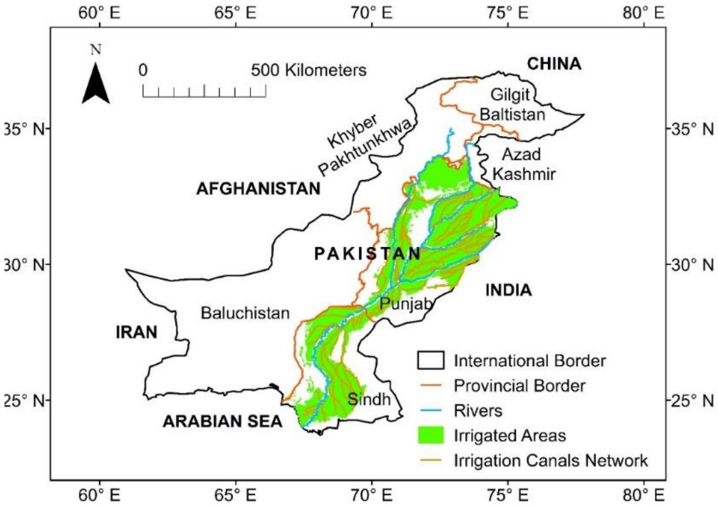

Figure 4.1 Map of the study area. The figure is generated in ArcGIS version 10.6.1 (https://www.esri.com/en–us/arcgis/products/index).

4.2 Materials and methods

4.2.1 Modeling framework

In this study, we develop an economic–environmental–modeling framework to evaluate the economic and environmental impacts of the status–quo irrigation practices and a variety of scenarios with IIT. The model is written in python by using the SciPy package. The modeling approach uses gridded data and makes use of information such as the irrigation requirements, harvested area, crop water consumption, groundwater level, energy use required for pumping water, water prices and energy costs. The methodological steps of the modeling framework are summarized in Figure 4.2, and the calculation methods are described in section 2.3. The input data used in this study are given in Table S–4.1 as a supplementary material.

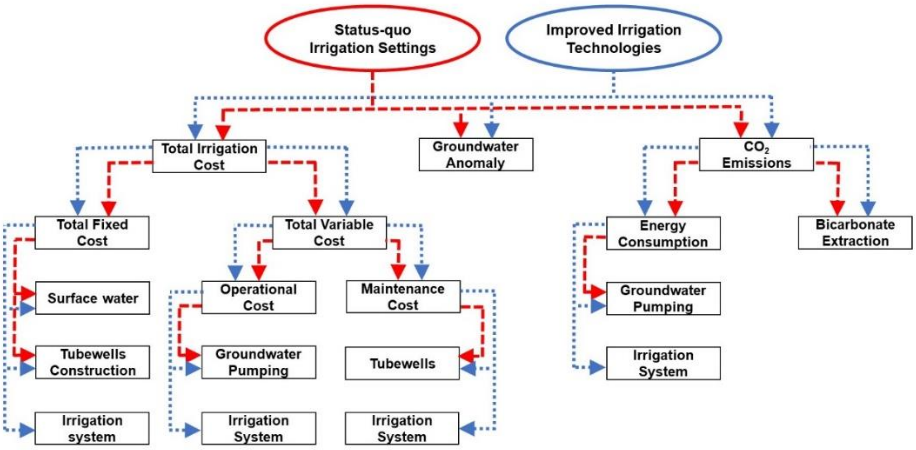

Figure 4.2 Methodological steps to estimate the economic and environmental impact of the status–quo irrigation settings and IIT.

4.2.2 Calculation methods

4.2.2.1 Irrigation requirements

The irrigation requirements (IRR_{area}) are calculated for the entire area by combining all crop's productive (IRR_{prod}) and unproductive (IRR_{unprod}) consumptions of irrigation water along with the leaching requirements (LR) (Eq4.1). IRR_{prod} contributes to crop growth, while IRR_{unprod} covers the water losses in line with the efficiency of the irrigation system (IRR_{effi}). IRR_{unprod} does not result in crop production and percolates from the root zone to the groundwater or evaporates at the soil surface. These water losses partially cover the LR (Multsch et al., 2013). The LR is an additional amount of water that is otherwise needed to leach salts from the root zone by assuming the salinity tolerance limit of each crop and the salt fraction in the irrigation water (Ayers and Westcot, 1985).

$$\mathbf{IRR_{area}} = \frac{\mathbf{IRR_{prod}}}{\mathbf{IRR_{effi}}} + \mathbf{LR} \qquad \text{(Eq4.1)}$$

with IRR_{area}, IRR_{prod}, and LR given in ($km^3\ yr^{-1}$) and IRR_{effi} in percentage (%).

In this study, we use data on the site−specific IRR_{prod} and LR (2002−2016) from a recently published study (Muzammil et al., 2020), where uncertainties in the input data have been quantified. The dataset holds information with a spatial resolution of 0.063° for Pakistan. Muzammil et al. (2020) used SPARE:WATER, an open−source model integrated into a geographical information system to estimate the crop water balance at the grid level (Multsch et al., 2013). SPARE:WATER follows the FAO56 guidelines to determine crop water requirements (Allen et al., 1998) and calculates the potential LR in line with the salinity tolerance limit of crops and the salt fractions in the irrigation water. For this study, we extended the simulation period of 2002−2016 from Muzammil et al. (2020) and included the years 2017 and 2018. A detailed list of model input data and parameters required to run the model is given in (Muzammil et al., 2020). The climatic data is obtained from the Pakistan Metrological Department, while information on crops is provided from the Pakistan Statistics Bureau. The efficiencies of irrigation systems are taken from the FAO dataset as 60%, 75%, and 90% for surface, sprinkler, and drip irrigation, respectively (Brouwer et al., 1985).

4.2.2.2 Surface water and groundwater use

As surface water and groundwater are used in the Indus basin to meet the irrigation demand, we estimate the surface water share ($km^3\ yr^{-1}$) from a dataset of annual canals supply. The data is preprocessed to exclude the off−farm water losses assuming a conveyance efficiency of 70% (Arshad et al., 2005; Cheema et al., 2014). The volume of groundwater abstraction ($km^3\ yr^{-1}$) is determined by subtracting the available surface water in the fields from IRR_{area}.

4.2.2.3 Irrigation costs

The total irrigation costs (TC_{area}; million US$ yr^{-1}) are estimated by adding the total fixed costs (TFC_{area}) and the total variable costs (TVC_{area}) (Eq4.2):

$$\mathbf{TC_{area} = TFC_{area} + TVC_{area}} \qquad \text{(Eq4.2)}$$

1) TFC_{area}

TFC_{area} are estimated by adding its components on a regional basis (Eq4.3), i.e., SWP_{area}, TCC_{area}, and irrigation system costs (ISC_{area}).

$$\mathbf{TFC_{area} = SWP_{area} + TCC_{area} + ISC_{area}} \qquad \text{(Eq4.3)}$$

where SWP_{area} (million US\$ yr^{-1}) results from summing up the products of costs occurring for surface water for crop irrigation (US\$ ha^{-1}) times their harvested area (ha yr^{-1}). TCC_{area} (million US\$ yr^{-1}) is estimated by dividing the initial costs of all tubewells (million US\$) for a given area from their average lifetimes (years). The initial costs of tubewells are projected by combining the construction costs of all diesel and electric operated tubewells. The TCC_{area} vary and depend on groundwater level and power required for pumping groundwater (Qureshi et al., 2010). ISC_{area} are calculated by summing up the product of all crops' irrigation system costs per hectare (US\$ ha^{-1}) times their harvested area (ha yr^{-1}). Note that the annual ISC_{area} are split in halves for the crops of the two growing seasons Kharif and Rabi, respectively. ISC_{area} are derived from dividing the initial costs of the systems by their average lifetimes (years). The status−quo irrigation system is based on gravity, therefore ISC_{area} for surface irrigation are negligible (Latif et al., 2016). The initial costs of the improved irrigation system vary from crop to crop and by changing the power source.

2) TVC_{area}

We use Eq4.4 to calculate the regional value of TVC_{area} by adding its components, i.e., the operational costs (OC_{area}) and the maintenance costs (MC_{area}):

$$\mathbf{TVC_{area} = OC_{area} + MC_{area}} \qquad \text{(Eq4.4)}$$

We further divide OC_{area} into two parts, i.e., the groundwater pumping costs (GPC_{area}) and the operational costs of the irrigation system (OCS_{area}). Accordingly, MC_{area} are composed of the maintenance costs of the tubewells (MCT_{area}), and the maintenance costs of the irrigation system (MCS_{area}).

The GPC_{area} (million US\$ yr^{-1}) is based on the costs for the energy sources diesel and electricity. The share of diesel and electric pumping in the study area is estimated by using the fraction of diesel and electric operated tubewells in a grid cell. GPC_{area} are projected by adding the groundwater pumping costs of diesel ($GPC_{area(d)}$) and electric ($GPC_{area(e)}$) operated tubewells. Both, $GPC_{area(d)}$ and $GPC_{area(e)}$, are calculated by summing up the product of the tubewell abstracted groundwater volumes (m^3) times the pumping costs (US$ m^{-3}). Pumping costs are calculated by multiplying the energy consumed (kWh) per m^3 pumped groundwater and the energy price (US$ kWh^{-1}). The energy consumption is determined from Eq4.5 where V, TDH, and η_{pp} are abstracted groundwater volume (m^3), total dynamic head (m), and pumping plant efficiency (%), respectively (Kay and Hatcho, 1992). In this study, the energy price for the electric source is used directly as the given electricity price in the country (US$ kWh^{-1}) while for diesel consumption, fuel price (US$ L^{-1}) is converted into an energy price (US$ kWh^{-1}) by multiplying fuel price with a conversion factor of 0.11 (Kay and Hatcho, 1992).

$$\textbf{Energy (kWh)} = \frac{\mathbf{V \times TDH}}{\mathbf{367 \times \eta_{pp}}} \qquad \text{(Eq4.5)}$$

The OCS_{area} (million US$ yr^{-1}) consists of the energy and labor costs of the irrigation system. The energy costs for the surface irrigation method are negligible as its operation is based on gravity (Khatri et al., 2013). For the pressurized irrigation system, energy demand is estimated by multiplying the energy required to run the irrigation system (kWh yr^{-1}) and the energy price (US$ kWh^{-1}), being either diesel or electricity. The energy consumption is estimated from Eq4.5 where TDH indicates the total head required to run the irrigation system, i.e., the operational head, friction losses, and suction lift. Labor costs are calculated by summing up the product of labor charges (US$ ha^{-1}) and the harvested area (ha yr^{-1}).
MCT_{area} (million US$ yr^{-1}) is calculated by summing up the annual maintenance costs of diesel and electric operated tubewells in the region. The maintenance costs of diesel and electric operated tubewells are estimated by multiplying the maintenance costs per tubewell and the number of electric and diesel operated tubewells in the study area.

Finally, the MCS_{area} (million US$ yr^{-1}) contains repair and cleaning costs of the watercourses, which is calculated by multiplying the maintenance costs (US$ ha^{-1}) and the total harvested area (ha yr^{-1}). For IIT, maintenance costs cover repair and security costs of the system. We estimate it as 5% of the total operational costs (Buchanan, 2002).

4.2.2.4 Groundwater storage

The annual aquifer recharge (mm) is estimated from the Water Table Fluctuation method by adding the groundwater storage anomaly (mm) and the depth of pumped groundwater from the aquifer (mm) (Bhanja et al., 2019; Wu et al., 2019). We use monthly terrestrial water storage data from the Gravity Recovery and Climate Experiment (GRACE) to estimate the groundwater storage anomaly. GRACE data has been validated for Pakistan in past studies (Iqbal et al., 2016; Tang et al., 2017). In this study, we apply the GRACE Mascon solution, which does not need post–processing filtering and which is less depending on scale factors (Save et al., 2016). Groundwater storage anomaly is derived by subtracting the surface water storage (soil moisture, canopy water, snow water) from the terrestrial water storage. The surface water storage is estimated up to 2 m of the soil column from the land surface model (NOAH) dataset of the GLDAS product, which has been used in several regions where in situ measurements are not available (Andersen et al., 2005; Leblanc et al., 2009; Rzepecka and Birylo, 2020; Tiwari et al., 2009).

Further, we calculate the contributions of the fields' percolation losses to total recharge. For the status–quo irrigation settings, it is estimated from published data (Arshad, 2004). This data is simulated via the GLEAMS hydrological model, which is used at the field scale to estimate the movement of water content through percolation and contribution of recharge to the groundwater (Nicks, 1998). Accordingly, water percolates from fields to the groundwater storage in the Indus basin of Pakistan at a rate of 0.314 mm day^{-1}. It is assumed that this percolation is negligible for IIT where irrigation surplus is marginal (Dewandel et al., 2008).

4.2.2.5 Carbon dioxide emissions

We estimate CO_2 emissions from the status–quo irrigation practices and IIT, where energy consumption and bicarbonate extraction from the groundwater are considered as the major emissions sources.

1) CO_2 Emissions from Energy Consumption

There are two energy consumption sources related to irrigation in the study area, i.e., groundwater pumping and irrigation system operation. CO_2 emissions are calculated by following the GHG protocols scope 1 (emission sources own or controlled by individual or company, i.e., fossil fuel consumption) and scope 2 (emissions from purchased electricity) (van der Hoek et al., 2018). The annual mass of CO_2 emissions depends on the amount of energy consumed (kWh yr^{-1}) and the types of these energy sources (Ramphull and Surroop, 2017), represented by their respective emission factors. We apply a fixed emission factor for diesel engines of 0.32021 kg CO_2 kWh^{-1} (Wang et al., 2012). For electricity, we calculate with a constant value of 0.47337 kg CO_2 kWh^{-1} based on information on the major energy sources for power production in Pakistan (Brander et al., 2011). Note that the status–quo irrigation system is based on gravity, therefore, no CO_2 is emitted.

2) CO_2 Emissions from Bicarbonates Extraction

In this study, we assume that the CO_2 concentrations in recharging groundwater and pumped groundwater are the same. If groundwater recharge is equal to the abstraction, there are no CO_2 emissions (Wood and Hyndman, 2017). Hitherto, CO_2 is emitted if groundwater is depleted and CO_2 is sequestered in the aquifer in cases of rising groundwater levels. We estimate CO_2 emissions/sequestration (million t CO_2 yr^{-1}) by multiplying CO_2 concentrations in the groundwater (mg L^{-1}) and groundwater depletion/increase (m^3). Groundwater depletion/increase is estimated by multiplying the groundwater storage anomaly (m) and surface area of the plain (m^2).

The CO_2 concentrations in the groundwater depend on atmospheric CO_2 dissolved in water, which enters the groundwater body via percolation and thus depends on the groundwater recharge rate. During solution, CO_2 and H_2O split into hydrogen (H^+) and bicarbonate (HCO_3^-) ions (Eq4.6).

$$\mathbf{CO_2 + H_2O \rightarrow H^+ + HCO_3^-} \qquad \text{(Eq4.6)}$$

It is assumed that half of the mass of total bicarbonates present in the groundwater originates from this separation. While another half is formed when the $CaCO_3$ rich rock in the aquifer reacts with hydrogen ions (H^+) (Mishra et al., 2018) (Eq4.7):

$$\mathbf{H^+ + CaCO_3 \rightarrow HCO_3^- + Ca^{2+}} \qquad \text{(Eq4.7)}$$

Depending on the resulting bicarbonate concentration in the groundwater, CO_2 evolves into the atmosphere according to Eq4.8 when groundwater is pumped.

$$\mathrm{Ca}\mathbf{(HCO_3)_2 \rightarrow CO_2 + H_2O + CaCO_3} \qquad \text{(Eq4.8)}$$

The resulting CO_2 concentration (mg L^{-1}) in the groundwater is calculated by multiplying the molecular mass ratio of HCO_3^- and CO_2 with the bicarbonate concentration (mg L^{-1}) (Eq4.9).

$$\mathbf{CO_2\ Concentration} = \frac{1}{2}\,\mathbf{HCO_3^-} \times \frac{44}{61} \qquad \text{(Eq4.9)}$$

4.2.2.6 Scenario development

We develop four future scenarios (SC−1 to SC−4) to derive a potential optimum plan for irrigation that reduces the irrigation costs, groundwater depletion, and CO_2 emissions in the Indus basin. Scenarios are established by changing the status−quo irrigation methods (gravity−fed surface irrigation) to IIT as this has been identified as a preferable solution to reduce total amount of irrigation water (Muzammil et al., 2020). The year 2018 is considered as a baseline to which scenarios are compared. We keep the harvested area from the baseline in the scenarios and convert surface irrigation to drip irrigation for row crops and to sprinkler irrigation for field crops. The scenarios are classified according to the energy sources required to operate the revised irrigation system. In SC−1, the diesel engines are used to operate the irrigation system, SC−2 is run on electricity but assumes subsidized prices as status quo conditions, SC−3 is also based on electricity, but considers the actual energy price, and SC−4 is defined by using solar energy.

4.3 Results

4.3.1 Water consumption and irrigation costs

The shares of surface and groundwater in irrigation water are shown in Figure S−4.1 as a supplementary material. The irrigation water consumption (IRR_{area}) and the total irrigation costs (TC_{area}) for 2002−2018 are presented in Figure 4.3. Results show that the southern part of Punjab has the highest IRR_{area} while the upper portion of Punjab and the whole parts of Sindh have relatively lower IRR_{area} (Figure 4.3a). We find strong inter−annual variation in IRR_{area} with the highest in 2002 (177 $km^3\ yr^{-1}$) and the lowest in 2015 (130 $km^3\ yr^{-1}$) (Figure 4.3b). A Mann−Kendall test reveals that there is no trend in IRR_{area} from 2002−2018 ($p = 0.23$). Average IRR_{area} is estimated to 157 $km^3\ yr^{-1}$, of which groundwater accounts for 52% (82 $km^3\ yr^{-1}$) and surface water contributes to 48% (75 $km^3\ yr^{-1}$). Diesel pumping has the largest share in groundwater abstraction with 83%, followed by electric pumping of 17%. Results of TC_{area} also show a substantial variation in space and year–to–year (Figure 4.3c,d). The southern region of Punjab has the highest TC_{area} compared to other parts of the study area (Figure 4.3c). The highest TC_{area} are calculated for 2014 (1,837 million US$) and the lowest one for 2003 (718 million US$) (Figure 4.3d). We find an overall significant increasing trend for TC_{area} from 2002–2018 ($R^2 = 0.43$, slope = 41.6, p=0.001). The years 2015 and 2016 are striking with lower costs, which are due to the combined effect of a lower IRR_{area} and reduced fuel prices compared to other years. The average TC_{area} for 2002–2018 are calculated to 1,301 million US$, of which fixed cost ($TFC_{area}$) components account for 8% (85 million US$) and variable costs ($TVC_{area}$) account for by far the largest amount (1,216 million US$). Groundwater pumping costs (GPC_{area}) have the largest share in TC_{area} with 60%, followed by maintenance costs (MC_{area}; 32%), surface water prices (SWP_{area}; 3%), and tubewell construction costs (TCC_{area}; 5%). Diesel pumping costs ($GPC_{area(d)}$) have a dominant part in GPC_{area} with 93%, while the electric pumping cost ($GPC_{area(e)}$) holds only 7%.

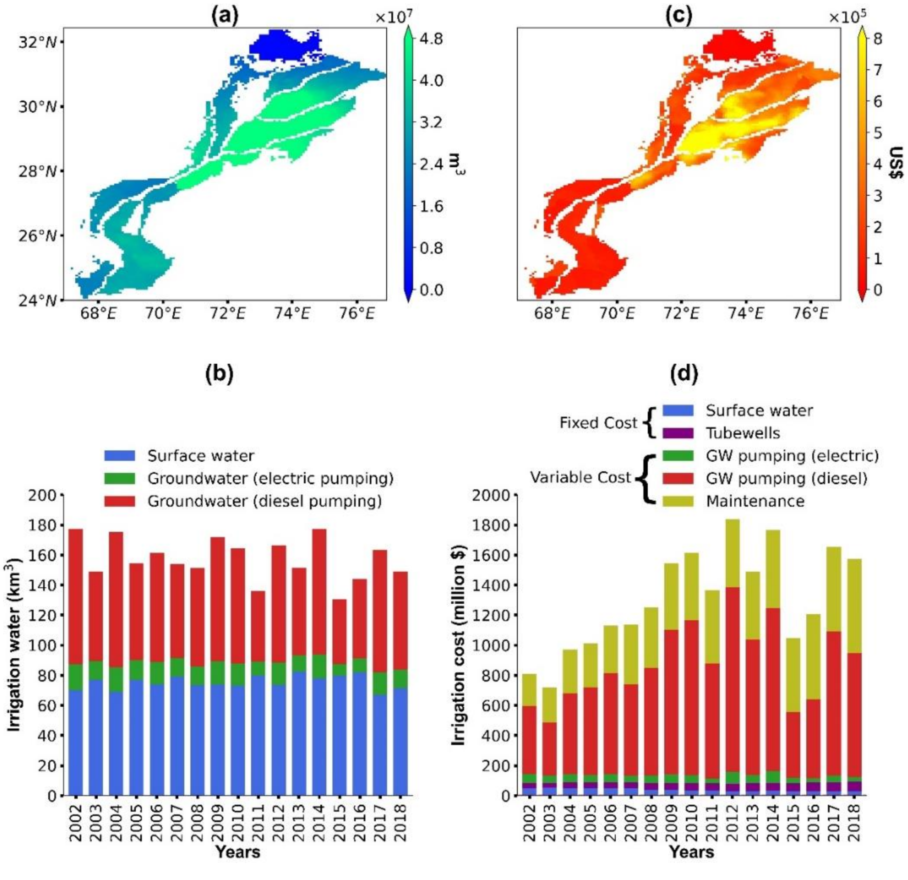

Figure 4.3 Irrigation water consumption (**a, b**) and irrigation cost (**c, d**) from 2002–2018.

4.3.2 Estimates of groundwater depletion

We project the groundwater storage from 2002–2018 by estimating the groundwater recharge and abstraction in the study area. The results show that the northern part of the plain (Punjab province) faces the largest depletion rate (−11 mm yr^{-1}) while an increase in groundwater level (4 mm yr^{-1}) is observed in the southern part of the plain (Sindh province) (Figure 4.4a). Overall, the groundwater storage anomaly is significantly decreasing ($R^2 = 0.39$, slope = −3.93, p=0.02) in the study area from 2002–2018 (Figure 4.4b) at a rate of −6.3 mm yr^{-1} (−1.35 km^3 yr^{-1}). Annual differences are substantial, with the highest depletion rate in the year 2018 (−78 mm yr^{-1}; −16.7 km^3 yr^{-1}) and the largest surplus in groundwater storage in 2003 (43 mm yr^{-1}; 9.2 km^3 yr^{-1}). Overall, we do neither find significant trends for net groundwater recharge (p = 0.06) nor for abstraction (p = 0.38). Further, the average net recharge rate is estimated to 380 mm yr^{-1}, of which 69% (263 mm yr^{-1}) are contributed by from natural resources (precipitation, and particular leaching from rivers, water bodies and canals) while the cropping fields add another 31% (117 mm yr^{-1}) as percolation losses from unproductive irrigation.

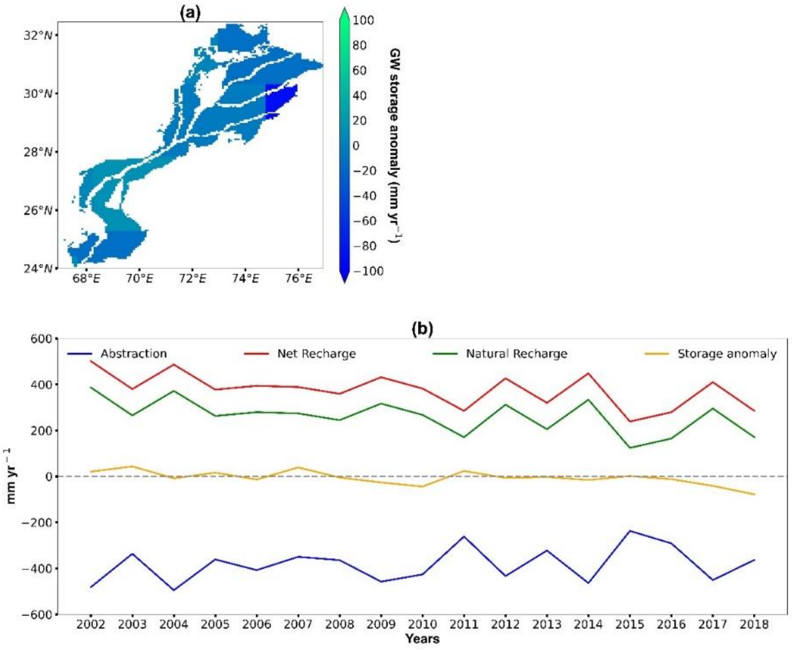

Figure 4.4 (**a**) Average groundwater depletion from 2002 to 2018, (**b**) Time series trend (2002–2018) of groundwater abstraction, net recharge, natural recharge, and storage anomaly.

4.3.3 Estimates of CO_2 emissions

We estimate CO_2 emissions from 2002–2018 according to the emission sources, i.e., energy consumption and bicarbonate extraction from depleted groundwater volume (Figure 4). The southern part of Punjab depicts the highest CO_2 emissions from energy consumption (Figure 4.5a) while the upper portion of Punjab shows the highest CO_2 emissions due to groundwater depletion (Figure 4.5b). The results further reveal that about 4.12 million t CO_2 yr^{-1} are emitted in the plain, of which 96% (3.95 million t yr^{-1}) result from energy consumption while 4% (0.17 million t yr^{-1}) are stemming from groundwater depletion. The largest CO_2 emissions are produced in the year 2018 (5.42 million t) and the lowest one in 2015 (2.15 million t) (Figure 4.5c). Further, CO_2 emissions from groundwater depletion are highly variable over time with a maximum in 2018 (1.58 million t). For several years, we found even negative values (i.e., an increase of the CO_2 storage) due to a surplus of groundwater recharge over groundwater abstraction. This results in rather substantial net storage of CO_2 in 2003 (−0.93 million t). With regard to the energy source, diesel pumping has a larger share (87%) than CO_2 emissions from electric pumping.

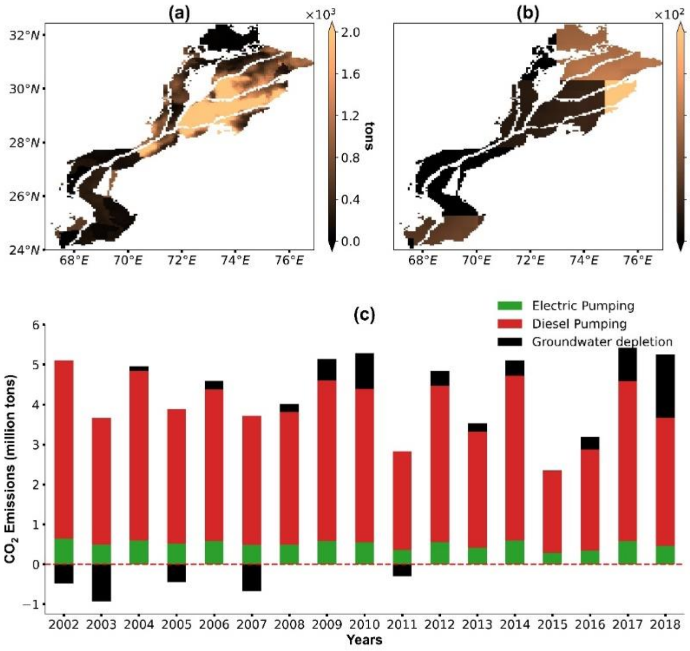

Figure 4.5 Average annual CO_2 emissions from (**a**) energy consumption and (**b**) groundwater depletion, (**c**) temporal development of CO_2 emissions from 2002–2018. (Note that the color–codes in the maps (a) and (b) vary by a factor of 10).

4.3.4 Scenario analysis

Scenarios are investigated to derive the optimum energy source for IIT and compare the results with the status–quo irrigation method. We establish four scenarios SC1–4 to identify the effect of IIT on TC_{area}, groundwater depletion, and CO_2 emissions for more sustainable irrigation practices by using different energy sources in each scenario. The changes in TC_{area}, groundwater depletion, and CO_2 emissions for all scenarios are presented in Figure 4.6 and Table S–4.2 as a supplementary material. In SC–1, we change the gravity driven status–quo irrigation settings with IIT and consider diesel as the primary energy source. The results indicate that TC_{area} and CO_2 emissions increase up to 170% and 410%, respectively, while the groundwater depletion is reduced by up to 135%. SC–2 focuses on changing the status quo irrigation settings with IIT that run on subsidized electricity from mains power. We find an increase in TC_{area} and CO_2 emissions of up to 63% and 165%, respectively. Meanwhile, the groundwater depletion rate decreases by up to 135%. The scenario SC–3 has the same settings as SC–2 but we use actual prices for electricity. In consequence, we observe an increase in TC_{area} of up to 130% of the baseline scenario. In SC–4, solar–powered IIT are used instead of the surface irrigation method. The results show that TC_{area} increase by up to 77% while CO_2 emissions and groundwater depletion are reduced by up to 81% and 135%, respectively.

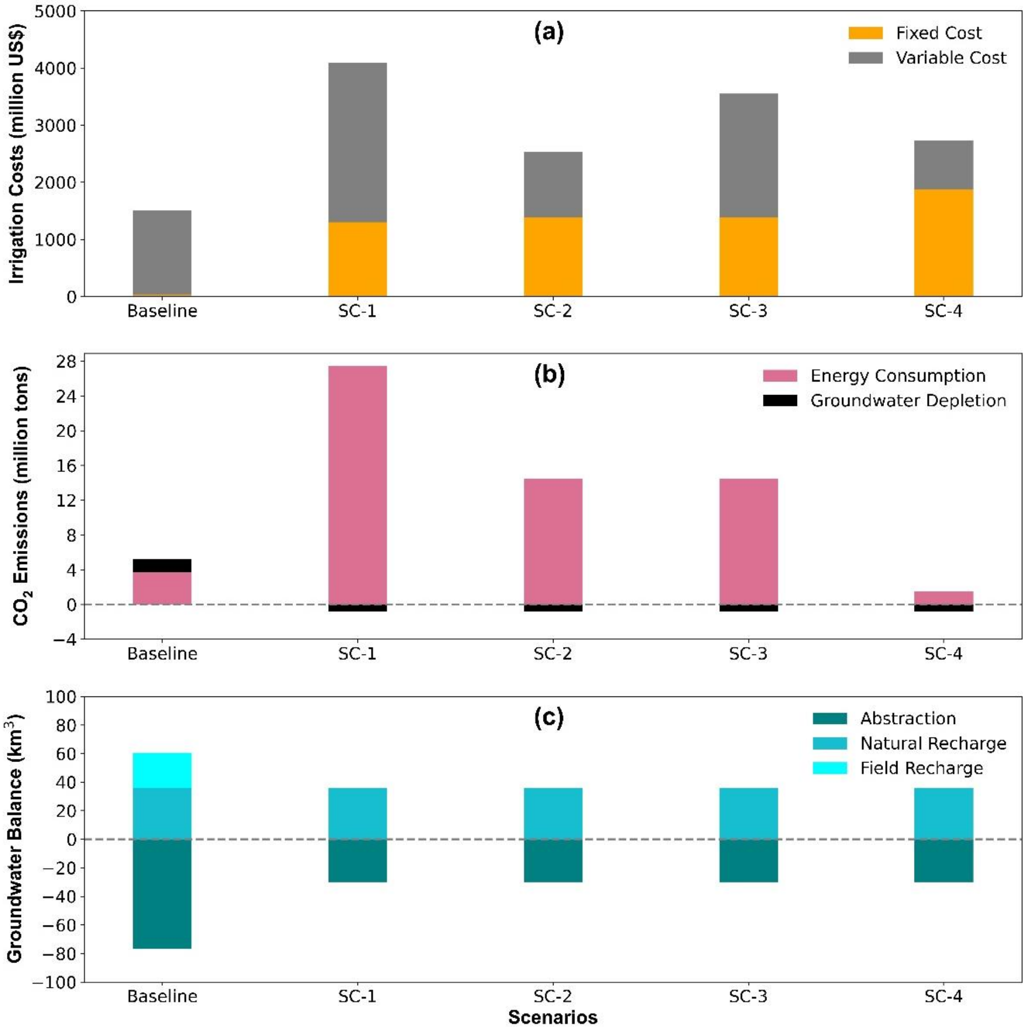

Figure 4.6 Scenarios analysis for (**a**) irrigation costs (**b**) CO_2 emissions and (**c**) groundwater balance, via IIT.

4.4 Discussions

4.4.1 Economic impact of irrigation methods

In the status−quo conditions, the average IRR_{area} in the study area is 157 km^3 yr^{-1}, of which surface water contributes 48% and groundwater 52%. Despite the small difference in water consumption from surface water and groundwater, there is a vast margin between prices with 3% for surface water and 63% for groundwater of TC_{area} (1,301 million US$), respectively. Alternatively, scenarios indicate that IIT can reduce IRR_{area} by 32%, which could lead to a reduction in groundwater share of up to 61%, with at the same time 55% decreasingGPC_{area}. However, IIT raise TC_{area} owing to the initial and running costs of the system. Scenarios specify that the operation of IIT via subsidized electricity is an optimal scenario among others for farmer's perspective where TC_{area} increase by 63% compared to the status quo. Solar energy is the second most feasible power source when no subsidized electricity is at hand, but still, TC_{area} increase by 77% compared to that of the status quo. Highest costs are found for diesel operated systems which boost TC_{area} by up to 170%. In short, the economic benefits of IIT are insufficient over the status–quo practices to cover the additional expenditure of the irrigation system. This is in line with various other studies that recognized that IIT can increase farmer's expenditures via capital investments and running costs (Huffaker, 2008; Pérez–Blanco et al., 2020; Soto–García et al., 2013) . For example, PARMAR and Thorat (2016) examined the barriers faced by farmers in India in adopting drip irrigation and found that the high initial cost is a major economic constraint to adoption of the technology. Rodrigues et al. (2012) studied the comparative advantages of drip and sprinkler irrigation in southern Brazil and concluded that economic benefits from water–saving technologies are insufficient to recover the initial costs of the system. Numerous studies revealed that the implication of IIT is a challenge owing to an extra burden of investment compared to surface irrigation. In Pakistan, despite the various awareness campaigns in the last three decades to introduce IIT, farmers are still not willing to adopt the technologies because of the high initial costs of the system. Thus, governments should provide subsidies to farmers for sustainable water consumption (Cremades et al., 2015; Liu et al., 2008; Tiwari and Dinar, 2002), such as in the World Bank funded Punjab Irrigated–Agriculture Productivity Improvement Project with a size of 50,000 ha. Such types of projects have the capability to promote water–saving technologies among farmers. However, it is doubtful that such a technical shift is sustainable from an economic viewpoint.

Part of this problem might be arising from the very low surface water prices in Pakistan, which do not promote changing towards more efficient, but costly irrigation technologies. Qamar et al. (2018) studied the implication strategies of IIT in the Indus basin of Pakistan and concluded that the surface water prices should be higher to promote IIT among farmers. We recommend that a comprehensive analysis should be conducted to study the adoption strategies of IIT by changing the water prices. Such an analysis should not only consider pure economic aspect, but also take into account societal barriers and personal preferences as well as choices from farmers.

4.4.2 CO_2 emissions from irrigation practices

We estimated CO_2 emissions from irrigation practices in the Indus basin of Pakistan by assuming emissions from energy consumption and bicarbonate extraction. At the status–quo settings, diesel or electric pumps are used to pump groundwater, which produces 96% of the total CO_2 emissions (3.95 million t). Our estimates indicate that bicarbonate extraction is not a significant emissions source, amounting to about 4% of the total CO_2 emissions (0.17 million t), although groundwater makes up a significant part of the irrigation water in the Indus basin. Mishra et al.(2018) estimated the annual CO_2 emissions from groundwater bicarbonate extraction to around 0.72 million t, which is not a significant emissions source either compared to energy consumption through groundwater pumping. Wood and Hyndman (2017) calculated CO_2 emissions from bicarbonates extraction in the USA and determined that annual 1.7 million t of CO_2 are released from this source. Despite a 10fold higher rate as compared to the groundwater mediated CO_2 emissions in the Indus basin, the total share of bicarbonate extraction on US CO_2 emissions is small with less than 0.5% (estimated from data published by (Wood and Hyndman, 2017).

Past studies proposed several strategies to reduce CO_2 emissions from groundwater pumping. For example, Shah and Kishore (2012) recommended on–site solar and wind energy for groundwater pumping. However, the authors show serious concern that the availability of renewable energy will encourage the farmers to pump additional groundwater because of the currently low pumping costs. Dhillon et al.(2018) projected that an improvement in pumping plant efficiency could also reduce CO_2 emissions. Zou et al.(2015) showed indirect effects through general water savings of improved irrigation systems and subsequent lower CO_2 emissions because of a reduced groundwater demand. However, IIT might require further energy to run the system, which in turn can increase overall CO_2 emissions. Daccache et al.(2014) studied the environmental impact of irrigation practices in the Mediterranean region of Spain. Similar to our results, they revealed that CO_2 emissions increased by 135% for IIT compared to the old–fashioned, gravity–based surface irrigation method.

We estimate CO_2 emissions for different scenarios of IIT by combining emissions from groundwater pumping and irrigation system operation. Our results indicate that diesel engines and mains power electricity are both detrimental energy sources for advancing irrigation technologies compared to the status−quo settings, simply because of the huge increase in CO_2 emissions by 410% and 165%, respectively. However, solar energy operating systems are most effective, which can reduce CO_2 emissions even of the status−quo technology by 81%. Many studies revealed that solar energy is the best option for IIT for sustainable development in a region or basin (Hartung and Pluschke, 2018; Roblin, 2016; Yang et al., 2014).

4.4.3 Groundwater depletion

In the study area, the average groundwater depletion is 6.3 mm yr^{-1}, which is comparatively low. For example, Long et al.(2016) estimated the groundwater depletion to 31 mm yr^{-1} in the Northwest Indian Aquifer. Shen et al.(2015) investigated groundwater storage anomaly in the Hai River Basin China and reported that groundwater is depleting at a rate of 17 mm yr^{-1}. Dangar and Mishra (2021) showed that groundwater depleted significantly during the period of 2002−2016 in the Ganga river basin India with a rate of 15 mm yr^{-1}. Voss et al. (2013) assessed the groundwater storage anomaly in the Tigris−Euphrates region of Iran by using GRACE data and projected that groundwater level drops at a rate of 17 mm yr^{-1}.Despite the lower depletion rate in the Indus basin, our estimates show that the groundwater depletion trend is increasing from 2002−2018. Tang et al.(2017) confirmed that groundwater storage is diminishing in the Indus basin. It has been predicted that the depletion rate in the Indus basin will increase by 50% in 2050 compared to the groundwater depletion trend in 2005 (OECD, 2017). We believe that an increasing trend of groundwater depletion is a serious matter and quick measures are needed for sustainable groundwater usage. In the sense of sustainability, the groundwater abstraction rate should be lower than the recharge rate (Cools et al., 2002; Foster and Garduño, 2004; Shamsudduha et al., 2011). Our results show that IIT are capable to reduce groundwater utilization compared to status−quo irrigation. However, such improvements can also have negative side effects like the reduction percolation losses from fields. These apparent negative losses lead, on the one hand, to a leaching of salts from the soil (Muzammil et al., 2020) and, on the other hand, also to groundwater recharge. Overall, our estimates verify that the reduction in groundwater abstraction is larger than field losses, resulting in an overall recharge of the groundwater body.

Our overall findings reveal that the status quo irrigation practices are favorable where groundwater depletion and CO_2 emissions are not such a problem, i.e., the lower part of the

Indus basin (Sindh). While IIT could be valued in areas where groundwater consumption is large (i.e., center Punjab), and where groundwater depletion rates, irrigation costs and CO_2 emissions are high. This is somehow contradicting the current national water policy of Pakistan, as the government is trying to implement IIT throughout the whole country (National Water Policy, 2018).This is because, the national water policy is based on the country's overall water management challenges without considering any spatiotemporal variability of the status quo irrigation practices and their economic and ecological impact . In line with our findings, we recommend that IIT should be adopted particularly in regional hotspots where the status quo irrigation practices have a strong negative environmental impact and the economic performance is particularly bad.

4.5 Conclusions

In this paper, we assess the economic and environmental impact of status–quo irrigation settings and alternative IIT in the Indus basin of Pakistan. We evaluate four scenarios by using different energy sources for improved irrigation systems and compare the overall outcomes with the status–quo irrigation method. Results indicate that a reduction in groundwater depletion is possible for all scenarios. CO_2 emissions can be reduced, particularly when solar energy is considered for power supply. For all other cases, the current status–quo is superior. We further show that irrigation costs increase in all scenarios compared to the status–quo. However, subsidized electricity is the preferable power source for IIT followed by solar energy, non–subsidized electricity, and diesel engines. From a cost–point view, we recommend solar energy as the second–best option for farmers if no subsidized electricity is available.

Apart from the benefits, the solar system might require a large area for panels installation, which could cause a reduction in the availability of cultivated land (Weselek et al., 2019). Nevertheless, state–of–the–art agro voltaic systems could offer a solution for the future, providing energy supply, reducing drought stress and water consumption and thereby improving water use efficiency (Amaducci et al., 2018; Weselek et al., 2019).

This study is conducted assuming the current boundary conditions of agricultural production in Punjab and Sindh, i.e., irrigation needs, available water and energy resources, as well as energy prices. In future studies, the impact of climate change, resulting glacier melt as well as demographic changes should be taken into account when developing sustainable irrigation practices for Pakistan. We also recommend that future estimates of irrigation costs should also include global CO_2 market prices by considering externalities of CO_2 emissions (Poelhekke, 2019).

Further aspects that should be picked up in future sustainability analysis are related to stakeholders and landowners. Our study does not consider any personal preferences and choices of farmers, which might result in barriers when adopting new irrigation technologies. And finally, rebound effects should also be considered when new technologies hit the market (Paul et al., 2019; Pfeiffer and Lin, 2014), particularly if water costs are low and solar powered pumping becomes an economic alternative on the long−term.

Supporting Information

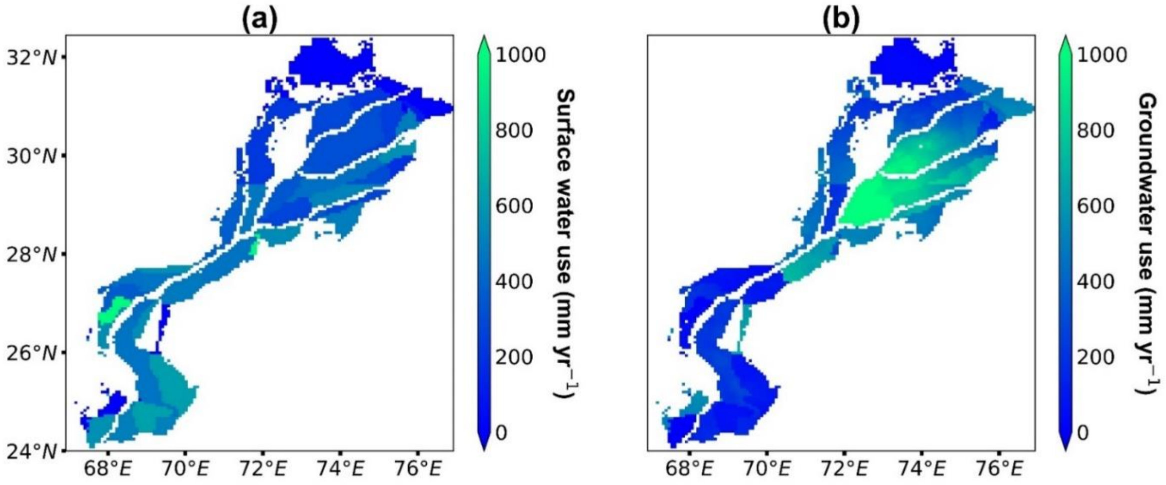

Figure S–4.1 (**a**) Surface water and (**b**) groundwater share in irrigation water consumption.

Table S–4.1 Model input data.

Dataset	Units	Resolution	Data Sources
Surface Irrigation			
Water price	US$ ha^{-1}	Spatial dataset	Pakistan Statistic Bureau (https://www.pbs.gov.pk/publications)
Labor and maintenance cost	US$ ha^{-1}	–	Directorate of Agriculture (Economics and Marketing) (http://www.amis.pk/Surveys.aspx)
Improved Irrigation			
System cost	US$ ha^{-1}	–	Punjab Irrigated Agriculture Productivity Improvement Project (PIPIP)
Pumping plant efficiency	%	–	Punjab Irrigated Agriculture Productivity Improvement Project (PIPIP)
Average lifetime	Years	–	(Razzaq et al., 2018)
Labor cost	US$ ha^{-1}	–	(Mian et al., 2019)
Maintenance cost	US$ ha^{-1}	–	(Buchanan, 2002)
Tubewells			
Density	diesel and electric fraction	Spatial dataset	Pakistan Statistic Bureau (https://www.pbs.gov.pk/publications)
Initial cost	US$	–	**(Qureshi et al., 2010)**
Average life	Years	–	(Johnson, 1982)
Pumping plant efficiency	%	–	(Pervaiz, 2010)
Groundwater lift	m	Point dataset	Irrigation and Power Department
Maintenance cost	US$	–	(Qureshi et al., 2003)
CO_2 Emission			
Groundwater depletion	mm yr^{-1}	Spatial dataset	GRACE (https://www.gfz−potsdam.de)
HCO_3 concentration	Mg L^{-1}	Point dataset	Pakistan Council in Research in Water Resources (http://pcrwr.gov.pk/water−quality−reports)
Emission factor	–	–	**(Brander et al., 2011)**,(Wang et al., 2012)
Miscellaneous			
Location of irrigated areas			(IWMI, 2018)
Conversion rate Pakistani rupee to US$	–	–	Pakistan Statistic Bureau (https://www.pbs.gov.pk/publications)
Electricity price	US$ kWh^{-1}	–	Pakistan Statistic Bureau (https://www.pbs.gov.pk/publications)
Diesel price	US$ L^{-1}	–	Pakistan Statistic Bureau (https://www.pbs.gov.pk/publications)

Table S–4.2 Scenarios analysis of IIT.

	Irrigation Costs (million US$)							Groundwater anomaly (mm)	CO_2 emission (million tons)		
	Fixed			Variable			Total		Energy consumption	Bicarbonates extraction	Total
	Surface water	Tubewells	Irrigation system	Operational		Maintenance					
				GW pumping	System operation						
Acronym	SWP_{area}	TCC_{area}	ISC_{area}	GWP_{area}	OCS_{area}	MC_{area}	TC_{area}				
Baseline	31	61	0	855	0	624	1,571	−780	3.7	1.6	5.3
SC−1	31	61	1,302	350	2,134	312	4,190	280	27.5	−0.5	27
SC−2	31	61	1,330	350	560	234	2,566	280	14.5	−0.5	14
SC−3	31	61	1,330	350	1,534	282	3,588	280	14.5	−0.5	14
SC−4	31	61	1,850	350	0	505	2,797	280	1.5	−0.5	1

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List of additional publications as co-author

Here is a list of all other publications that I have been working on alongside my thesis.

Afzal, M.A., Ali, S., Nazeer, A., Khan, M.I., Waqas, M.M., Aslam, R.A., Cheema, M.J.M., Nadeem, M., Saddique, N., Muzammil, M., Shah, A.N., 2022. Flood Inundation Modeling by Integrating HEC–RAS and Satellite Imagery: A Case Study of the Indus River Basin. Water 14, 2984. https://doi.org/10.3390/w14192984

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Declaration

Ich erkläre: Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der „Satzung der Justus−Liebig−Universität Gießen zur Sicherung guter wissenschaftlicher Praxis" niedergelegt sind, eingehalten.

I declare that I have completed this dissertation single−handedly without the unauthorized help of a second party and only with the assistance acknowledged therein. I have appropriately acknowledged and cited all text passages that are derived verbatim from or are based on the content of published work of others, and all information relating to verbal communications. I consent to the use of an anti−plagiarism software to check my thesis. I have abided by the principles of good scientific conduct laid down in the charter of the Justus Liebig University Giessen „Satzung der Justus−Liebig−Universität Gießen zur Sicherung guter wissenschaftlicher Praxis" in carrying out the investigations described in the dissertation."

Giessen, 06 May 2024

Muhammad Muzammil