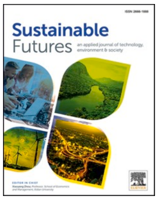
Sustainable Futures 11 (2026) 101959

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures



A System Dynamics Simulation Model for Sustainable Water Resources Management in Pakistan

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ARTICLE INFO

Keywords:
Water resources management
system dynamics modelling
regional conflict
Scenarios analysis

ABSTRACT

Water resource management for sustainable development is complex due to interactions between socio-economic, natural, and demographic factors. Effective management requires integrating environmental and socio-economic considerations and their feedback loops. This study developed an integrated simulation model using system dynamics to explore interactions between Pakistan's population, industry, agriculture and water resources subsystems. The model serves as a learning tool for policymakers, providing understanding of long-term water resource dynamics and evaluating policy scenarios for sustainable management and economic growth. Water resource management is complex due to intertwined feedback among socio-economic, environmental, and demographic factors. This study developed an integrated system dynamics model to explore long-term interactions between Pakistan's population, industry, agriculture, and water resources. The model aids policymakers by providing insights into policy impacts. Simulation results show that under business-as-usual conditions, the water supply-demand gap could increase 5.5-fold by 2050, compared to 2000 levels (52.54 BCM). This finding indicates restricting water use alone is insufficient given expected growth. Under a comprehensive scenario integrating demand-side measures with enhanced water infrastructure investment, the model predicts a 38% reduction in water deficit and 21% GDP improvement versus baseline, demonstrating how integrated strategies can foster economic growth while mitigating the water gap.

1. Introduction

Water is a vital resource essential for human survival and socio-economic development. However, the growing water demands driven by population growth and climate change are projected to outstrip supply by 40% by 2030 resulting in over 1.8 billion individuals residing in regions of absolute scarcity [1]. This will devastate agricultural output and global economic growth, particularly in developing countries. Pakistan is among the most susceptible nations in this regard. The per capita availability of renewable water resources has significantly decreased from 5,000 CM in 1951 to 1,102 CM per person in by 2018 [2], which is considerably below the international water stress threshold of 1,700 CM per person. Economically, the agricultural sector, which contributes 22% to the GDP and employs over 37% of the labor force, utilizes more than 90% of Pakistan's freshwater withdrawals [3]. Environmentally, excessive groundwater extraction in Punjab and Sindh is leading to annual water table declines of 0.5–1 m[4], while climate change poses a threat to reduce Indus River flows by up to 30% by mid-century [5] . Socially, the lack of access to safe drinking water already impacts nearly 70% of households in certain regions, prompting rural–urban migration and exacerbating poverty [6]. These statistics highlight the critical need for the development of a comprehensive national framework for water resource management. Managing water resources for sustainable development is a highly complex undertaking because it cuts across socio-economic drivers, hydrological cycles, and diverse demands from competing sectors [7–9]. This complexity is further intensified by the dynamic interactions and feedback loops that link social, environmental, and demographic processes, making it difficult to predict the long-term outcomes of management decisions [10]. Understanding these interconnections is therefore essential; overlooking them can lead to misguided policies that weaken system resilience and increase vulnerability [11].Feedback mechanisms, in

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https://doi.org/10.1016/j.sftr.2026.101959
Received 24 December 2024; Received in revised form 20 September 2025; Accepted 2 June 2026

particular, are now recognized as critical determinants of how human–environment systems sustain themselves over time [12].

Despite their importance, research that explicitly addresses these feedback processes and their role in resilience remains relatively limited. In response, scholars have argued for adopting a holistic perspective that accounts for the interdependence between socio-economic dynamics and water resource systems [12–17]. Such an approach enables more sustainable and efficient management by recognizing the complexity of these interactions [18]. At the national scale, this means water management strategies must be both comprehensive and integrated, acknowledging the links between environmental processes and social and economic systems [19–22]. It also requires that emerging pressures such as population growth and climate change be incorporated into water policy and planning.

Over the past six decades, system dynamics modeling (SDM) has emerged as one of the most effective tools for analyzing such complex, interconnected systems [9,23]. SDM is grounded in an integrated perspective that captures how biophysical, social, and economic processes interact dynamically and respond to change [24–26]. Because of this ability, it has been widely applied to study water management challenges across different basins, cities, and regions worldwide [27–31]. System dynamics modeling has been used to gain a clear understanding like sustainable water resource management in river basins [10,32,33]. The system dynamics model has been applied in a number of studies for provincial [34–37] and the city level water resources management [38–42]. Despite the vast number of areas in which system dynamics has been utilized to manage water resources, there is still a need for a model that reflects the interaction and feedback loops between different socio-economic, natural and demographic factors associated with sustainable water resources at the country level. Existing country-scale models are mainly undertake the hydrological aspects of the basin and the economic factors related to agriculture, while socio-economic dynamics are often ignored and not quantitatively incorporated into the analysis [25,43–45]. Consequently, the long-term dynamic behavior of water resources on the country level is vaguely understood.

This paper presents an integrated system dynamics simulation model for sustainable water resource management at the country level for Pakistan. The model is designed to optimize water resource management by providing predictions and evaluating the potential outcomes of different management strategies, thus improving the overall effectiveness of the management process. This research contributes to the field in several ways as shown in Fig. 1.

The model developed in this study operates at the national scale and integrates multiple subsystems, including population, agriculture, industry, and both surface and groundwater resources. By building a simulation-based system dynamics (SD) framework, the study provides a decision-support tool that can assist policymakers and water managers in pursuing sustainable resource strategies. In addition, the research applies scenario analysis to quantitatively explore how Pakistan's water system responds to different policy and development pathways. Through this scenario-based approach, the model captures how the system evolves under varying assumptions about key drivers over time, thereby offering a richer understanding of long-term water dynamics and their implications for planning.

The model's central purpose is to reveal how different subsystems within the broader water system interact and influence one another, while also identifying the most critical leverage points that shape system performance. Insights generated from these simulations can inform more evidence-based and sustainable water management policies at the national level. More broadly, the study advances the literature by applying a holistic, integrated perspective to the management and

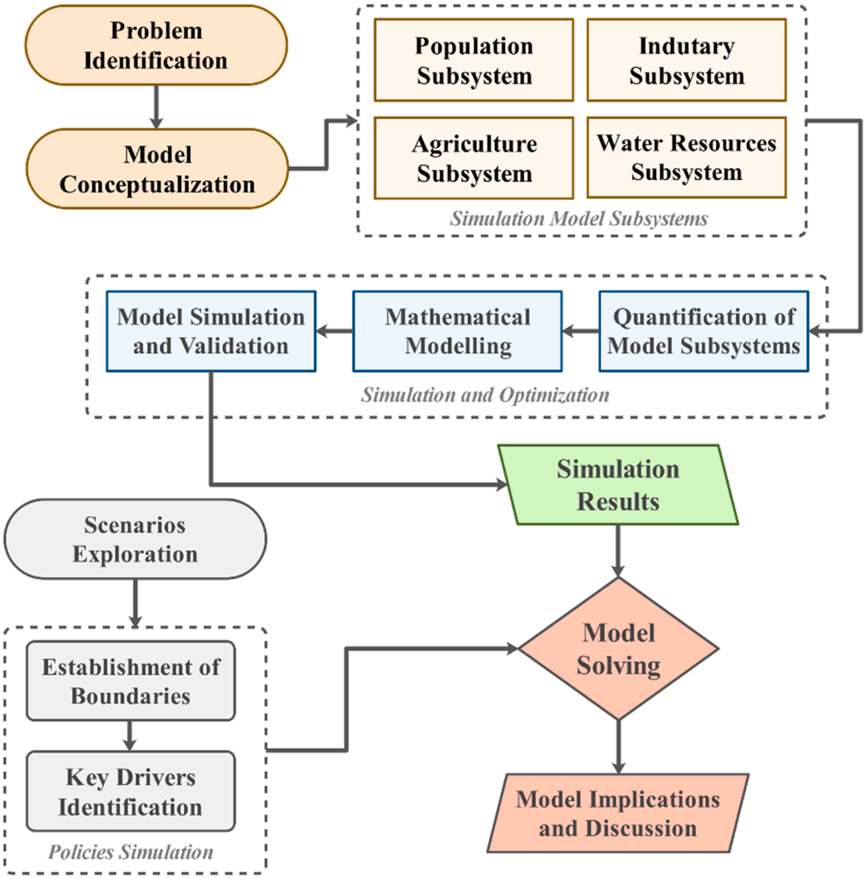

Fig. 1. Framework of SD Simulatino Modelling.

allocation of water resources, thereby contributing to ongoing debates on sustainable governance in water-stressed contexts.

The structure of this paper is organized as follows: Section 2 delineates the scope and context of the study, encompassing the characteristics of Pakistan's water resources and historical trends. Section 3 provides a review of pertinent literature on water management modeling and the application of system dynamics. Section 4 details the methodology and model architecture. Section 5 presents the results of baseline and policy scenarios, discussing their implications and offering comparative international insights. Section 6 concludes with the key findings, highlights the innovations and limitations of this research, and proposes directions for future research.

2. Scope of the study

Despite being one of the world's most arid nations with an average annual rainfall of less than 240 millimeters and the fourth highest rate of water use [46], Pakistan relies largely on the sole water source "Indus River System". The Indus River is a significant watercourse in South Asia, the source of which comes from the Himalayas, Karakoram, and Hindu Kush mountain ranges located in Tibet, India, and Afghanistan (Fig. 2). The river's main stem runs through Kashmir, divided between India and Pakistan. The Indus Basin, which encompasses the provinces of Punjab, Sindh, and Khyber Pakhtunkhwa (KPK) in Pakistan, covers over 65% of Pakistan's total land area of 520,000 km^2. Additionally, nearly 300 million people in India and Pakistan depend on the Indus Basin's water resources[47]. Egypt and Pakistan may be the only ones more dependent on a single river basin in the world's top populated countries.

In Pakistan, the agricultural sector plays a significant role in the economy, accounting for 22.7% of the country's Gross Domestic Product (GDP) and providing employment, both directly and indirectly, for 37.4% of labor force [48]. Pakistan's economy relies heavily on water from the Indus River, and managing water resources is crucial. India and Pakistan's competition for the limited water resources of the Indus River Basin has long been a cause of tension between the two countries. As a lower riparian, Pakistan must manage the water supply of upper riparians Afghanistan and India [49]. In the years after Pakistan's liberation from British rule in 1947, the country's economy encountered several challenges. Punjab's irrigated heartland was cut off from the life-giving waters of India's Ravi, Beas, and Sutlej rivers during the partition of the Indo-Pak subcontinent. In April 1948, India severed Pakistan's water supply access, leading to further deterioration of the situation. A treaty between Pakistan and India was signed in 1960, guaranteeing Pakistan's rights to three western rivers—the Jhelum, Indus, and Chenab—to use their water for irrigation purposes. As a result, India gained full control over the three eastern rivers (Beas, Sutluj, and Ravi). India already violated the treaty by constructing run-of-river dams on the western rivers (Salal, Dumkhar, Chutak, Kirthai, Sawalkot, PakalDul, and Bursar dam) on the Chenab river [50].

Pakistan's available water supply has dropped from 5,000 CM per capita in 1951 to 1,102 CM per person in 2018 [51]. Pakistan is moving from a "water-stressed" to "water-scarce" country according to the water scarcity indicator (as shown in Table A.1) [52,53]. Water availability exhibits significant regional variation across Pakistan. The provinces of Punjab and Sindh, which are integrated into the Indus Basin Irrigation System (IBIS), benefit from extensive canal networks and relatively higher water allocations. In contrast, Balochistan and Khyber Pakhtunkhwa experience chronic water shortages and are heavily dependent on groundwater resources. In certain southern districts of Sindh, over two-thirds of rural households lack reliable access to drinking water [6], while Punjab is experiencing declining aquifer levels due to intensive tube-well irrigation practices [4]. These regional disparities complicate water management efforts, necessitating policies that balance inter-provincial equity with national sustainability. While Pakistan's total renewable water resources have remained fairly constant around 140 MAF annually the pressures of rapid population growth, agricultural intensification, and climate change have made scarcity increasingly acute. Over the past two decades, groundwater extraction has risen sharply, with nearly 70% of aquifers in Punjab now considered overexploited [4]. Weak governance and unsustainable management practices have further compounded the challenge. The widening gap between supply and demand is not the result of a single factor but rather the outcome of intertwined drivers, including demographic growth, urban expansion, climate variability, agricultural demand, and limited recognition of the links between socio-economic and environmental processes. To ensure sustainable and resilient management, long-term planning must explicitly address these interconnections, as they play a central role in shaping the challenges faced by water managers. Although several recent studies have examined water availability and use in Pakistan particularly for domestic and agricultural needs, or in relation to climate impacts on livelihoods they have often overlooked the system's non-linear dynamics and feedback processes over time [22,45,54–56]. This research therefore contributes by developing an integrated model that captures the influence of key socio-economic drivers population, agriculture, industry, and environmental factorson water resources management at the national scale. These long-term trends elucidate the evolution of Pakistan's water crisis and provide essential context for the scenario analysis conducted in this study.

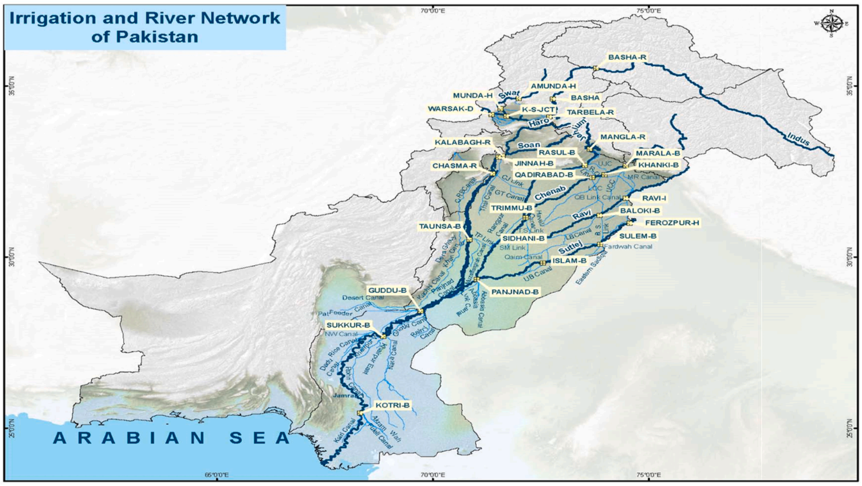

Fig. 2. Rivers and Irrigation Network in Pakistan (Source: Adapted from IRSA, 2018).

3. Methodology

3.1. System dynamics modeling approach

System Dynamics Modeling (SDM) is a state-of-the-art computerized method that utilizes the principles of feedback control and non-linear dynamics to comprehend and imitate complex systems [57]. System Dynamics Modeling (SDM) is built on the premise that systems display nonlinear behaviors and time lags. The Stanford Watershed Model, developed by Crawford and Linsley [58], is widely considered as one of the first thorough simulation models for watershed management and was developed shortly after the development of SDM. Winz et al. [59] extensively studied the use of SDM in water resource systems. Given its ability to analyze non-linear dynamics of primary feedback systems, SDM has been chosen to study Pakistan's water resources in this research. SDM provides the benefits of both continuous and discrete time principles and makes it suitable for non-linear modeling dynamics, such as water resources systems [9,60].

System Dynamics Modeling (SDM) was selected over alternative modeling methodologies due to its comprehensive, feedback-oriented approach, which is well-suited for large-scale integrated analyses. While Agent-Based Models (ABM) are effective in capturing micro-level behaviors, they become computationally demanding at a national scale and offer limited transparency for policy evaluation [61]. Econometric models, although adept at capturing statistical relationships, struggle to represent feedback mechanisms or temporal delays. Pure hydrologic simulation models are beneficial for assessing basin-level water balances but often overlook socio-economic factors. In contrast, SDM facilitates the integration of socio-economic and hydrological subsystems within a single framework, rendering it an appropriate tool for addressing Pakistan's water resource challenges.

This study also references the concept of the stated preference method. In economics, stated preference approaches, such as contingent valuation, involve soliciting individuals to express their willingness to pay or preference for hypothetical changes or policies [62]. Although we did not conduct such surveys directly, the concept informed the design of demand-side assumptions, particularly regarding behavioral responses to conservation measures. Consequently, the model indirectly incorporates preference-related considerations, adapted from existing studies rather than original surveys.

This methodological approach substantiates the selection of SDM as the most appropriate framework for assessing the interconnected socio-economic and environmental dynamics of water resources in Pakistan

Furthermore, SDM strategy helps reveal the dynamic nature of complex systems behaviour over time instead of presenting a static picture [9,23,63]. An SD model begins with a conceptual model, which is followed by stock and flow diagrams (often abbreviated as SFD), which are used to quantify and simulate the model [9]. Fig. 3 illustrates the conceptual model of water resources balance of Pakistan.

Previous research employing system dynamics modeling (SDM) in the domain of water management has yielded significant insights while also revealing notable limitations. For example, Kotir et al. [64] effectively utilized SDM in the Volta River Basin in Ghana, successfully capturing the interactions between agricultural and hydrological systems. Similarly, Liu et al. [65] applied SDM to model lake water quality in China, illustrating its utility for watershed management. However, both studies were confined to subnational contexts, thereby limiting their applicability to national-scale planning. In Pakistan, Ahmed et al [66] simulated irrigation water supply and land-use change within the Indus Basin, yet their model predominantly focused on hydrological aspects, with limited integration of socio-economic feedbacks. Likewise, Janjua et al. [67] examined water management challenges in Pakistan but offered only qualitative assessments without employing dynamic modeling. These gaps underscore the necessity for a national-level, integrated SD model that encompasses cross-sectoral feedbacks among population, industry, agriculture, and water resources. By addressing this gap, the present study advances the field both methodologically and substantively, providing a more comprehensive approach than previous efforts.

3.2. Model development and subsystems

Conceptual models depict the causal relationships between key variables in a system, but they are typically qualitative and cannot be utilized to replicate the behavior of the system over time. System Flow Diagrams (SFDs) provide a numerical foundation for System Dynamics Models [57,68]. The fundamental assumption of principle of Stock and Flow Diagram (SFD) is that systems can be depicted as a combination of stocks (accumulated quantities) and flows (rate of changes), where material is accumulated in stocks and moved between them by means of flows [69]. Based on the interaction between subsystems and feedback loops, four subsystems, i.e., population, agriculture, industry, and water resources, have been used to evaluate the influence on water conservation following the footsteps of [10,70–72]. Fig. 4 illustrates the model

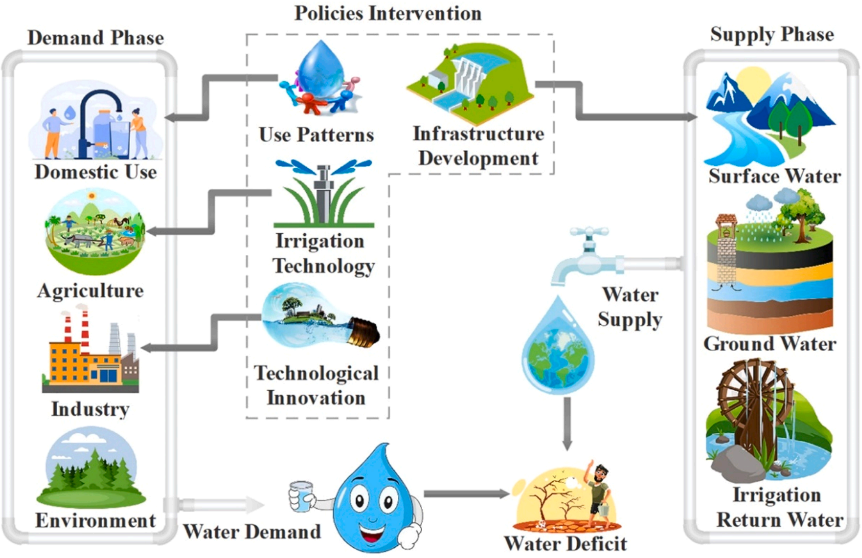

Fig. 3. Conceptual water balance diagram of Pakistan water system.

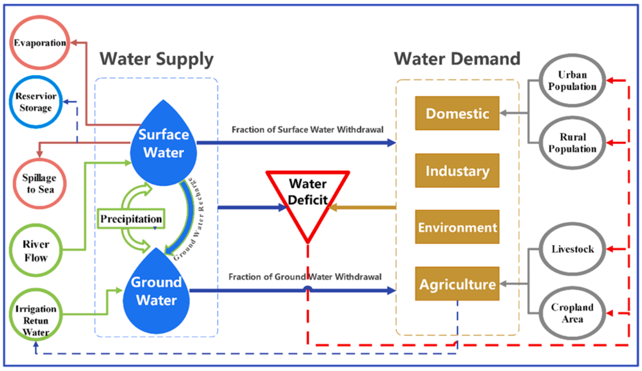

Fig. 4. Model Structure.

structure for comprehensively assessing the sustainability of water resources. The model is described in more detail below and SFD displayed in Appendix (Fig. A.1,Fig. A.2,Fig. A.3).

3.2.1. *Population subsystem*

The population directly influences water resources and economic development [73]. Pakistan has identified population growth as the most significant socio-economic driver impacting the use and availability of water resources. The total water demand is comprised of both rural and urban water demand, linked to the population level, as well as the per capita water consumption. Following Yang et al. [74] the present study includes three primary variables that adequately indicate the population's size and growth rate: total population, urban population, and rural population. Immigration and emigration are not considered since movement across areas has little effect on the total population. In addition three major indicators (birth rate, death rate and urbanization) are considered in model to show the scale and growth rate of population. Urbanization is important indicator to consider because of different water use pattern in rural and urban population.

3.2.2. *Agriculture subsystem*

Land and water resources management are inextricably linked, and this interaction is regarding the utilization of both resources [75]. One of the primary contributions of our study is the inclusion of agricultural land resources and livestock as a critical component of sustainable water resource use, as the agriculture sector is the major consumer of water in Pakistan. As a result, the agricultural subsystem's indicators include the area distribution of cropland. Some indicators are: food demand, cropland area (Net cropland + permanent crops area), added cultivated area, maximum cultivatable area, number of livestock, meat demand, and growth. The stock variable in this subsystem is the total cropland area and total livestock population, whereas the rate variable is the growth rate at which new farmland is developed and the growth rate of livestock.

3.2.3. *Industry subsystem*

The country's economic development content represents agricultural production and industrial output, which rely heavily on water resources. Demand for water resources is not only interlinked with economic development but also influences the capacity of water supply resources. Consequently, economic factors should be reflected in the subsystem of the economy's industry structure. A few indicators have been chosen for this analysis to represent the industrial subsystem best, the rise in industry's output and value-added.

3.2.4. *Water resources subsystem*

The water resource subsystem is the study's primary system, and it is divided up into the supply side and the demand side. The region's overall water resources come from various sources, including its surface and groundwater supply. Numerous factors influence water demand, including domestic consumption, agriculture, industry, and ecology. Designing and constructing the water resources subsystem took into account the hydrological cycle of water. A number of factors, including stock variables, rainfall, rate variables, and water return from renewable sources determines the yearly expansion of surface water resources. Contrarily, evapotranspiration, groundwater recharge, the consumption of surface water as a result of the total water demand and spillage to sea contribute to a decline in the amount of accessible surface water resources as represented in Eq.(1).

$$SWR(t) = \int_{t0}^{t} \left(W_{RF} + W_{P} - W_{DD} - W_{AD} - W_{ID} - W_{ENV} - W_{GR} - W_{EVP} - W_{Spill} \right) dt \tag{1}$$

Where, the river flow from the eastern, western and Kabul rivers is represented by W_{RF}, W_P shows the water recharge from precipitation, W_{DD} domestic water demand, W_{AD} agriculture water demand, W_{ID} industrial water demand, W_{ENV} environmental water demand, W_{GR} groundwater recharge and W_{EVP} Evaporation. W_{Spill} represents the unstored water flows into the Arabian sea.

Groundwater resources are another stock variable that increases by surface water recharge, precipitation, agricultural return water and decreases when the rate of groundwater consumption rises in response to growing demand and an increasing volume as shown in Eq. (2).

$$GWR(t) = \int_{t0}^{t} \left(W_{GR} + W_{P} + W_{IR} - W_{DD} - W_{AD} - W_{ID} - W_{EN} \right) dt \tag{2}$$

Where, W_{IR} represents the irrigation return water

Surface water and groundwater resources comprise the comprehensive water supply resources (Eq. 3).

$$W_{Supply} = SWR + GWR \tag{3}$$

Water demand estimation is based on the quantity needed for agriculture (irrigation and livestock), as well as for household (rural and urban), industrial, and environmental usage (Eq. 4).

$$W_{Demand} = WD_{Domestic} + WD_{Agriculture} + WD_{Industry} + WD_{Environment} \tag{4}$$

3.3. *Data and model parameter*

The data selected from 2000 to 2017 from different sources as population and demographic estimates were approximated using the economic survey of Pakistan [76]. Cropland area and crop yields data was gathered from the Economic Survey of Pakistan- Agriculture section and FAO [48,77]. The Indus River System Authority (IRSA) and world bank reports and published sources provided the data for accessible surface water, reservoir storage capacity, and demand [78,79]. The Pakistan Indus Basin SD model was parameterized using the data of the year 2000. Table A.2 in apendix summarizes the model's primary parameters and their associated values. The simulation model has been used in this study is version 6 of Vensim DSS.

3.4. *Scenarios design*

In order to effectively utilize water resources in a sustainable manner, various scenarios have been developed which take into account the unique impact of different subsystems. Key decision variables, including the level of urbanization, growth rate of industry, industrial water usage, and irrigation quotas, have been carefully selected and used to design specific policy scenarios. These scenarios are designed to help guide decision-making and promote sustainable water resource utilization.

3.4.1. *Business-as-usual*

The 'Business-as-usual' scenario, also called the baseline, demonstrates that neither development policies nor system structure will significantly change throughout the projection period.

3.4.2. *Population growth scenario*

Population growth is a key driver of water demand and supply. Changes in population growth have direct and indirect impacts on water resources, with direct effects on rural and urban water demand, and indirect impacts on agricultural and industrial water consumption through increase in output. Urbanization also shapes water demand, with water consumption in urban areas typically higher than in rural areas [80]. The combined effects of population growth, urbanization, and economic development can lead to an imbalance in water resources, particularly as it relates to lifestyle-related excessive water consumption [7]. This highlights the importance of considering population growth and urbanization as a key driver in water resource management and decision-making.

3.4.3. *Agriculture leading scenario*

Agriculture is the major consumer of water in Pakistan, accounting for more than 80% of total water consumption in Pakistan [75]. The rapid growth of Pakistan’s population has placed mounting pressure on food demand, driving the expansion of cultivated land to increase agricultural output. To capture the effects of this trend, the study models an increase in agricultural land development alongside improvements in crop yields. At the same time, advances in irrigation practices such as drip, sprinkler, and precision irrigation offer opportunities to enhance water-use efficiency and reduce overall consumption in the agricultural sector [45]. Accordingly, the analysis also incorporates the role of technological innovation and modern irrigation methods. By examining both agricultural expansion and the adoption of water-saving technologies, the study provides insights into how population-driven food demand affects water resources and evaluates the potential of efficiency-oriented interventions to mitigate these pressures.

3.4.4. *Industry growth scenario*

Pakistan has made industrial growth a top priority in recent years as a way to boost economic development [81]. The importance of industrial growth for economic development in Pakistan is highlighted in this scenario. To forecast the industry's water consumption till 2050, an increase in the industrial GDP growth rate is taken into account. Implementing water saving technologies and recycling of wastewater reduce industrial water withdrawal, increase water efficiency, and ultimately save costs for industrial companies. Implementation of water-saving technologies is assumed to be integrated with industrial development to analyze the reduction in water consumption per dollar. This approach aims to ensure sustainable water usage in the industrial sector while promoting economic growth.

3.4.5. *Economic expansion scenario*

The prior two scenarios demonstrate the individual effect of agricultural and industrial growth on the water supply and demand gap. The economic expansion scenario considered the combined effect of agricultural and industrial growth rates to emphasize economic development and its impact on water resources management. Economic development has remained the top priority of Pakistan for the present and most likely be so for the future for a very long time. Modern water-saving irrigation and technologies have also been considered with economic expansion.

3.4.6. *Dry Conditions*

Global warming is one of the major threats faced by the earth and all living habitats. Environmental changes have resulted in a shift in the national average temperature and rainfall pattern. In the next 50 years, melting glaciers in the western Himalayas are expected to increase Indus River flows. Once the glacial reserves are depleted, flows could drop by 30–40% during the following 50 years [82]. This uncertainty makes it difficult to predict the impact of climate change on the Karakoram glaciers and the Indus River flow. Considering the current ratio of global warming 40% decrease in rainwater recharge has been considered to forecast the water dynamics for the future. Global drought events can cause an annual reduction of up to 10% in cropland area [83] . The impact of climate change on Pakistan's agriculture sector has been studied in terms of changes in crop yields and land use to anticipate future changes in water resources.

3.4.7. *Kashmir Conflict Expedition*

Pakistan heavily relays on a single water source, the "Indus basin river system," for most of the country's requirements. More than 80% of the water supply comes from the Indus Basin River system, which originated from India, which has serious conflict over Kashmir and fought four wars. Though the Indus water treaty (1960) divides the water usage of different rivers between India and Pakistan, continuous violation by India has been attempted. Further development of dams or expedition of the Kashmir conflict may reduce the water supply for Pakistan [50]. A reduction in water supply has been assumed in the conflict expedition scenario to forecast Pakistan's future water supply availability.

3.4.8. *Infrastructural Improvements*

In this scenario we have considered increased in dams capacity for more water storage capacity for future perspective. According to Water and Power Development Authority (WAPDA), several new projects are underway to increase the overall water storage capacity in Pakistan. These projects include the construction of the Diamer-Bhasha Dam, Mohmand Dam, Dasu Hydropower Project, Nai Gaj Dam, Sindh Barrage, and K-IV Project [84]. These efforts are expected to increase gross water storage from 13 million acre-feet (MAF) to more than 24 MAF, an increase of 11.7 MAF. This additional water storage capacity is expected to provide several benefits, including the ability to irrigate an additional 1.6 million acres of land and provide 950 million gallons of water per day for drinking purposes to the cities of Karachi and Peshawar. These efforts demonstrate a clear commitment to addressing water scarcity issues in the region and are expected to significantly impact the livelihoods and well-being of those living in the affected areas.

3.4.9. *Comprehensive Scenario*

The comprehensive scenario considered sustainable economic growth with limited water conservation resources. Considering the different industrial and agricultural growth rates and water quotas, forecast the future water supply and demand. Table A.3 in appendix tabulates all scenarios.

4. Results

4.1. *Model testing*

Model calibration is an essential step in testing the applicability of the developed model before conducting simulations. To ensure the accuracy and reliability of the model, it is calibrated using several tests proposed by Barlas [85] and Sterman [9] such as a parameter-confirmation test and a dimensional consistency test. These tests measure the model's ability to accurately simulate the real system.

To perform the calibration, observed data of selected parameters (rural and urban population, cropland area, and industrial output) from 2000 to 2017, as per data availability, was used. Three statistical metrics, namely maximum relative error (M), coefficient of determination (R2), and discrepancy coefficients (U0) were used to assess the concordance between the observed data and the simulated values of the chosen parameters [86]. These statistical measures provide an objective assessment of the model's performance, and the results are used to evaluate the model's ability to accurately simulate the real system.

$$M = \frac{\sum (X_m - X_d)}{\sum X_d} \tag{5}$$

Eq. (5) represents the Maximum possible divergence between model simulated data(X_m) and historical data(X_d).

$$R^2 = \left(\frac{COV(X_m - X_d)}{\sigma X_m - \sigma X_d}\right)^2 \tag{6}$$

R^2 range from 0 to 1, a value closer to 1 indicates the well-fitted behavior of the model.

$$U_0 = \frac{\sqrt{\sum (X_m - X_d)^2}}{\sqrt{\sum X^2{}_m} + \sqrt{\sum X^2{}_d}} \tag{7}$$

Where, U_0 range from 0 to 1, a value closer to 0 indicates the well-fitted behavior of the model.

The results of the calibration tests demonstrate that the developed model is capable of accurately simulating the water resource system (Fig. 5). This demonstrates the model's viability for use as a decision-making tool in achieving sustainable management of a country's water resources.

Table A.4 illustrates that the model accurately captures the current trends and changes in industrial production, as evidenced by the error rate not exceeding the 10% significance level for several years[87]. Furthermore, consistent results from testing the model with various variables suggest that it effectively replicates the data. Overall, the study suggests that system dynamics models can be effectively utilized to simulate economic data.

4.2. Simulation and forecasting

Based on the model fitting outcomes, we simulated the SD model of Pakistan's water resources management and economic development.

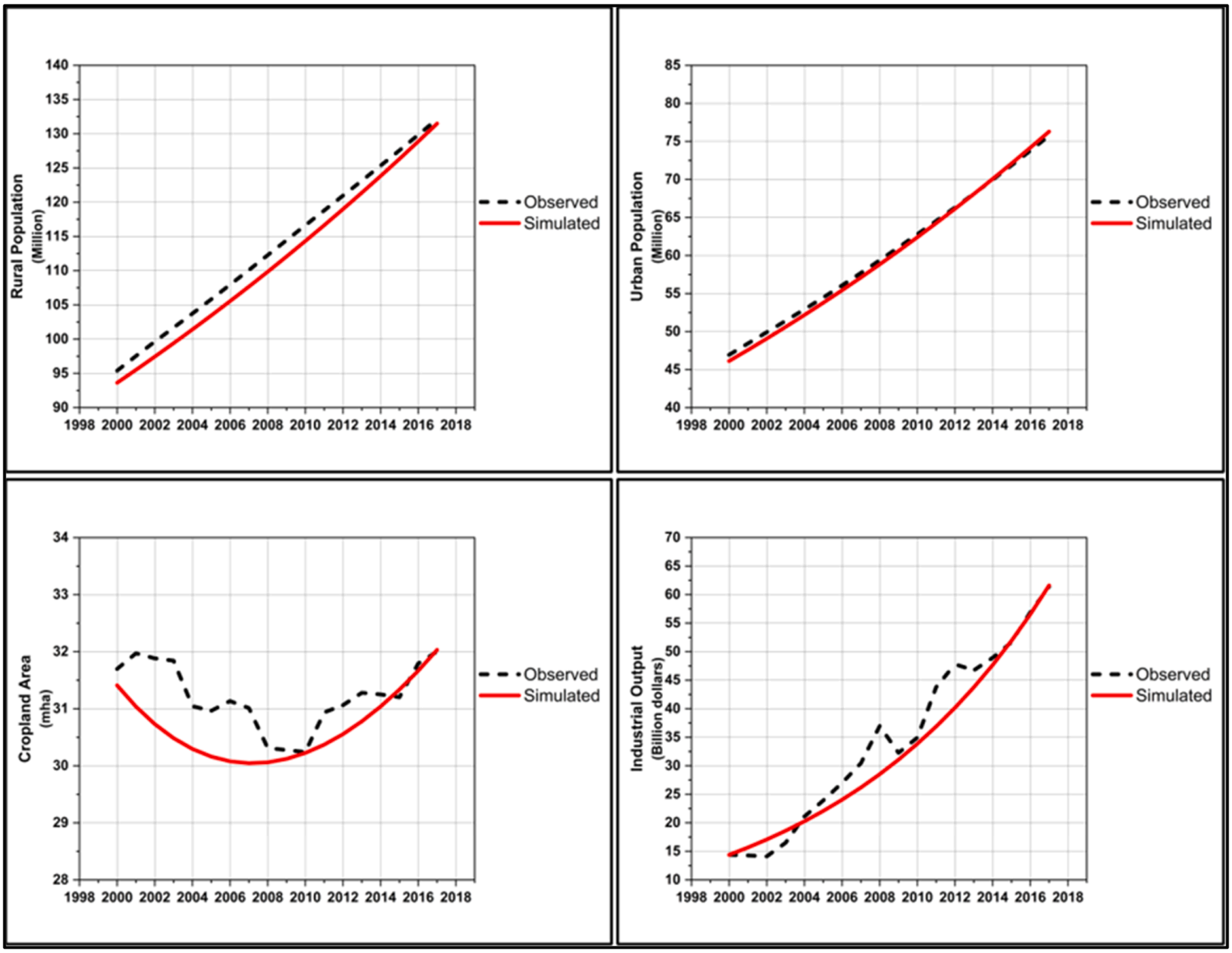

Fig. 5. Comparison between historical and simulated values.

Table A.5 tabulates the results of all the model subsystems from 2000 to 2050. In the population subsystem, a high growth rate in urban and rural populations can be observed. The increase in the urban population is around 4 times greater than the increase in the rural population, and the total population is expected to reach 358.93 million by 2050. The growth rate of livestock is greater than the cropland area, with 6 times growth in 2050. The cropland area in the agriculture subsystem shows positive but less growth due to the constraints of the cropland area.

The rate of increase in the agriculture subsystem is the lowest. The maximum arable land is considered based on currently available land for agriculture. The restricted agricultural growth is due to cropland constraints, and the results are aligned with Kotir et al. [10] for the Volta river basin. The industrial subsystem, among all subsystems, showed the highest growth rate. Only a negative growth rate can be observed in the water subsystem. Water supply during the simulation period decreased, while water demand grew by 35%. Growth in other subsystems, like industry, agriculture, and population, directly and indirectly affects water demand. Increasing water demand over time due to rapid growth in other subsystems (population, agriculture, industry) and decreasing water supply risen water deficiencies. Fig. 6 demonstrates the baseline simulation till 2050. Sun et al. [72] demonstrated a similar negative relationship between agricultural and industrial growth and water resources availability in China. Water supply and demand gap is expected to increase to 5.5 times in 2050, indicating the crucial need for effective ways and policies to shorten this gap by improving water supply and implementing efficient water resource use.

4.3. Simulation for designed policy scenarios

In this section, all the socio-economic scenarios developed earlier are simulated. Analyzing the effect of all subsystems individually and the combination of multiple subsystems on the exploitation of water resources is essential, as different subsystems influence sustainable water use in different ways. Pakistan is amid an extreme water crisis, the causes of which are complex and include many different elements. Due to the widening disparity between supply and demand, increased water use efficiency is essential. Fig. 7-9 shows the simulation results of different scenarios and comparisons with baseline simulation. The impact on sustainable utilization of water resources has been tested under various conditions to analyze the effect of every subsystem. "S0" indicates the business-as-usual scenario in which all the parameters and growth rates are considered on an ongoing basis and not changed. The effect of an increase in population growth rate on sustainable utilization of water resources has been simulated under "S1", which shows that the 10% increase in population growth increases the municipal/domestic water demand by 13.33%, indicating the highest domestic water demand among all scenarios (Fig. 7). An increase in population also indirectly impacts the water by increasing the need for more food and cultivation land area, which requires more water. However, the high growth rate in the population may place pressure on the environment and resources; a population control policy is suggested in "S2," with a 10% decrease in growth rate for a more sustainable situation.

The impact of expansion on economic growth has been simulated under S3 and S5 (Fig. A.4), indicating agricultural and industrial growth, respectively. S7 demonstrates the overall economic growth by combining both agriculture and industrial subsystems (Fig. 8).

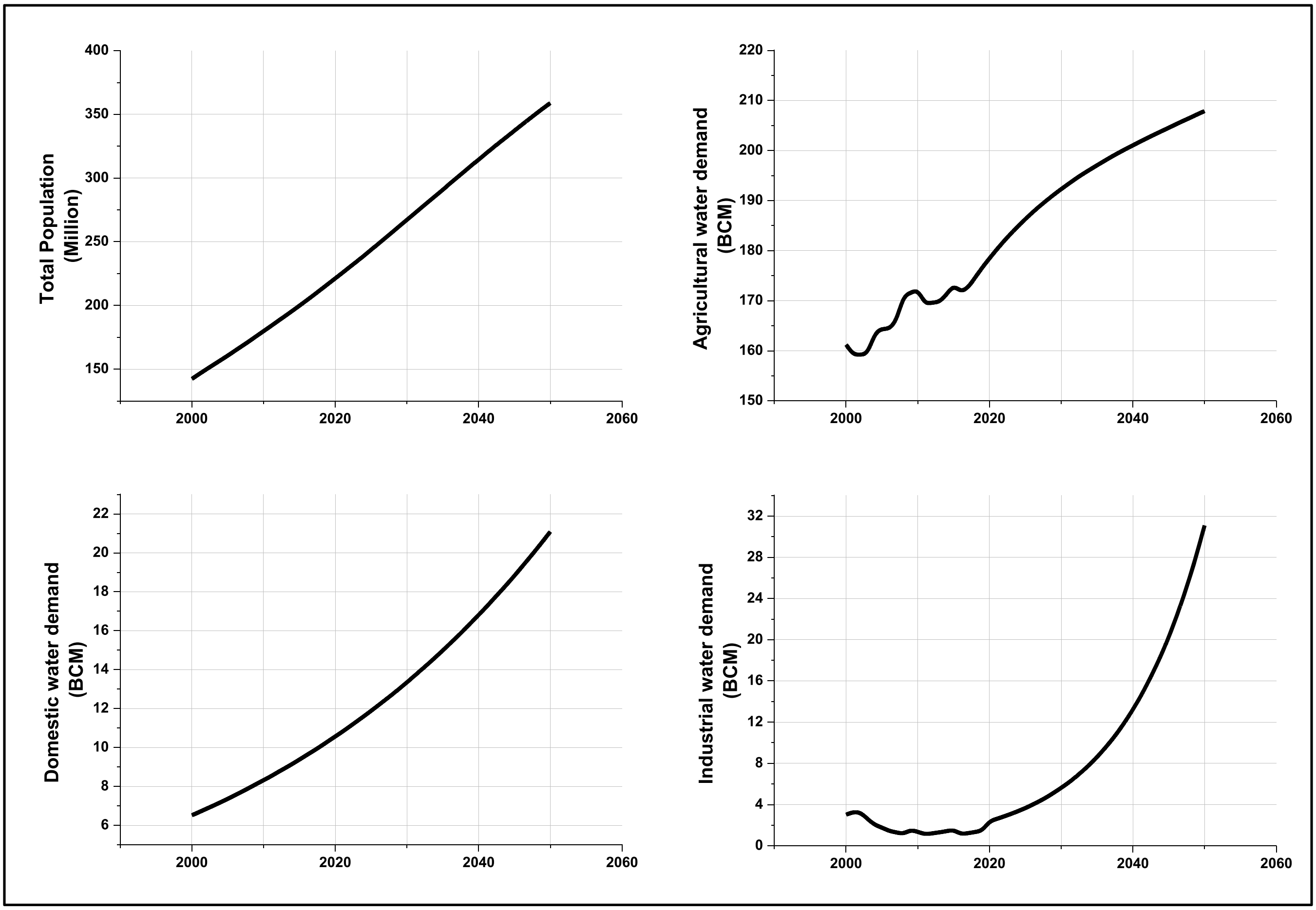

Fig. 6. Baseline simulation.

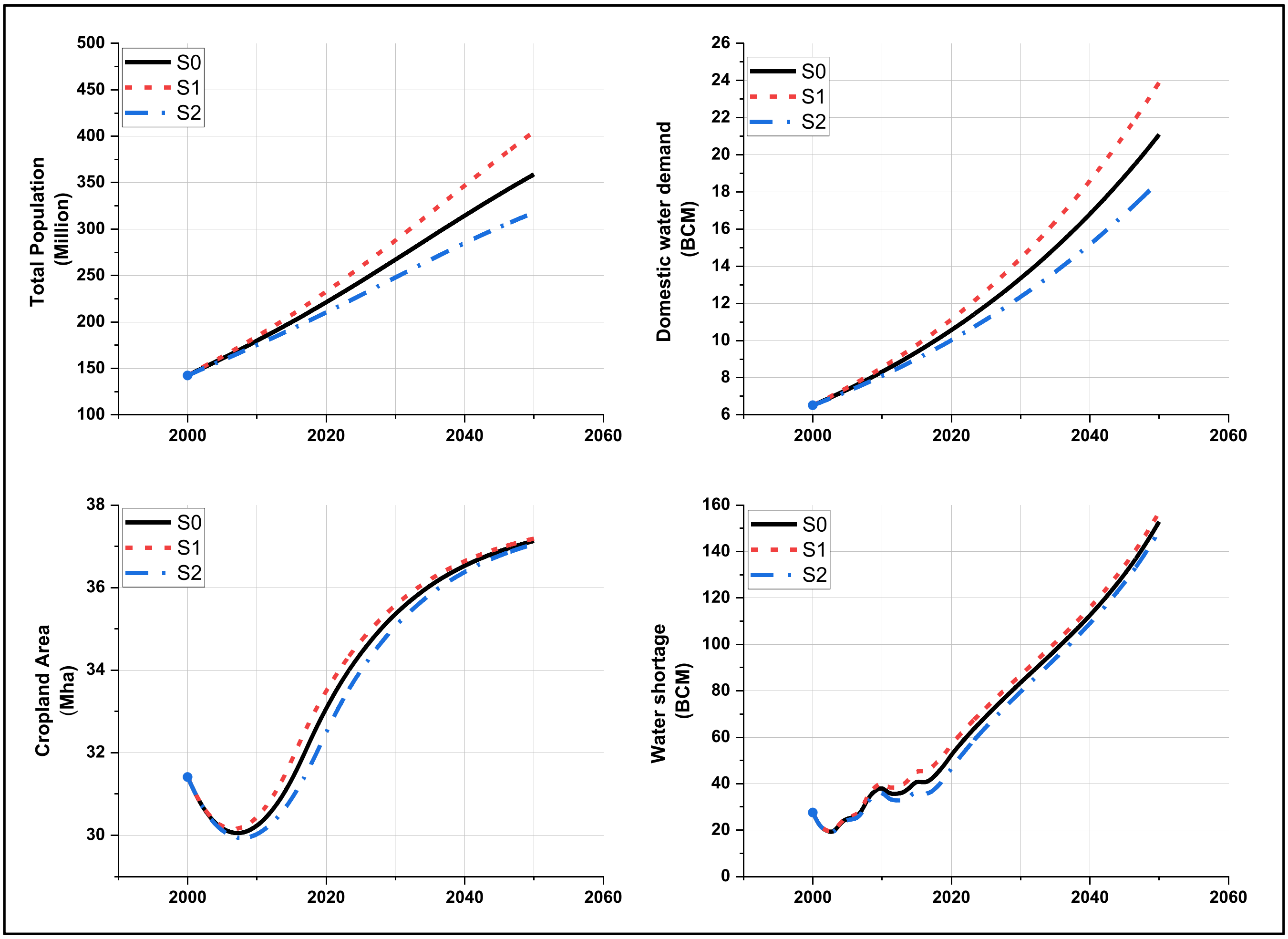

Fig. 7. Population growth scenario results.

Compared to S3 and S5, S7 shows the highest economic growth . By expanding cropland area by 10% and crop yield by 10%, the economy may get a suitable agricultural sector expansion to fulfill local food needs. Without considering sustainable water resources management, this expansion will come with a great cost in the shape of an ample water supply and demand gap. S7 shows the baseline model's largest water demand and supply gap of over 40%. A similar trend of water shortage due to increasing agricultural growth to get future food security can be observed in the study by Bhatti et al. [88]. Water-saving technologies in agriculture and the industrial sector play an essential role in water conservation [89]. The role of water-saving irrigation techniques and technological improvement has been analyzed in S8 with economic expansion.Fig. 8.

Different simulation results showed few significant differences in water supply, indicating that the gap between water demand and supply is mainly from the demand side. Water demand changes significantly due to changes in several subsystems, and there are significant shifts in the gap between water supply and demand. To analyze the impact of the supply side on the water demand and supply gap, S9, S10 and S11 have been simulated with a decrease in water supply considering the dry conditions and escalation in the Kashmir conflict (Figs. A.5 and A.6). Pakistan mainly relies on a single water resource, the "Indus River Basin," which started from the Tibted plateau and entered Pakistan via India and Kashmir. Any conflict may result in a severe water crisis for Pakistan. Recent events like the Pulwama attack (14 February 2019) escalated the heat among both nations and caused a great problem. A 50% decrease in water supply in the rivers with an inflow stream from India has been simulated to demonstrate the impact of reduced water supply on Pakistan's water crises and economic development. S11 showed the lowest water supply among all scenarios. Infrastructural improvement to save more water from spillage to sea has been analyzed in S12, depicting the significant reduction in water deficit [56]. For balanced economic growth by considering the sustainable utilization of water resources, S13 has been suggested as a more suitable solution (Fig. 9).

The observed trends not only indicate numerical changes but also highlight the socio-economic factors influencing Pakistan's future water landscape. For instance, the significant rise in water demand under the business-as-usual scenario is attributed to rapid population growth and urbanization, coupled with unregulated industrial expansion and inefficient irrigation practices. These elements, already evident in Pakistan's urban centers and agricultural regions, elucidate the steep increase in demand despite a stagnant supply.

Conversely, the comprehensive scenario illustrates how coordinated interventions can alter systemic dynamics. Investments in extensive storage infrastructure and canal rehabilitation directly enhance supply, while policies promoting water-saving irrigation and wastewater reuse mitigate demand growth. These measures operate through reinforcing feedback loops: improved efficiency alleviates pressure on groundwater, thereby stabilizing aquifers that would otherwise decline, and consequently sustaining agricultural productivity. The model thus demonstrates how real-world policy shifts such as government-led infrastructure projects and regulatory frameworks interact with socio-economic development to influence long-term outcomes.

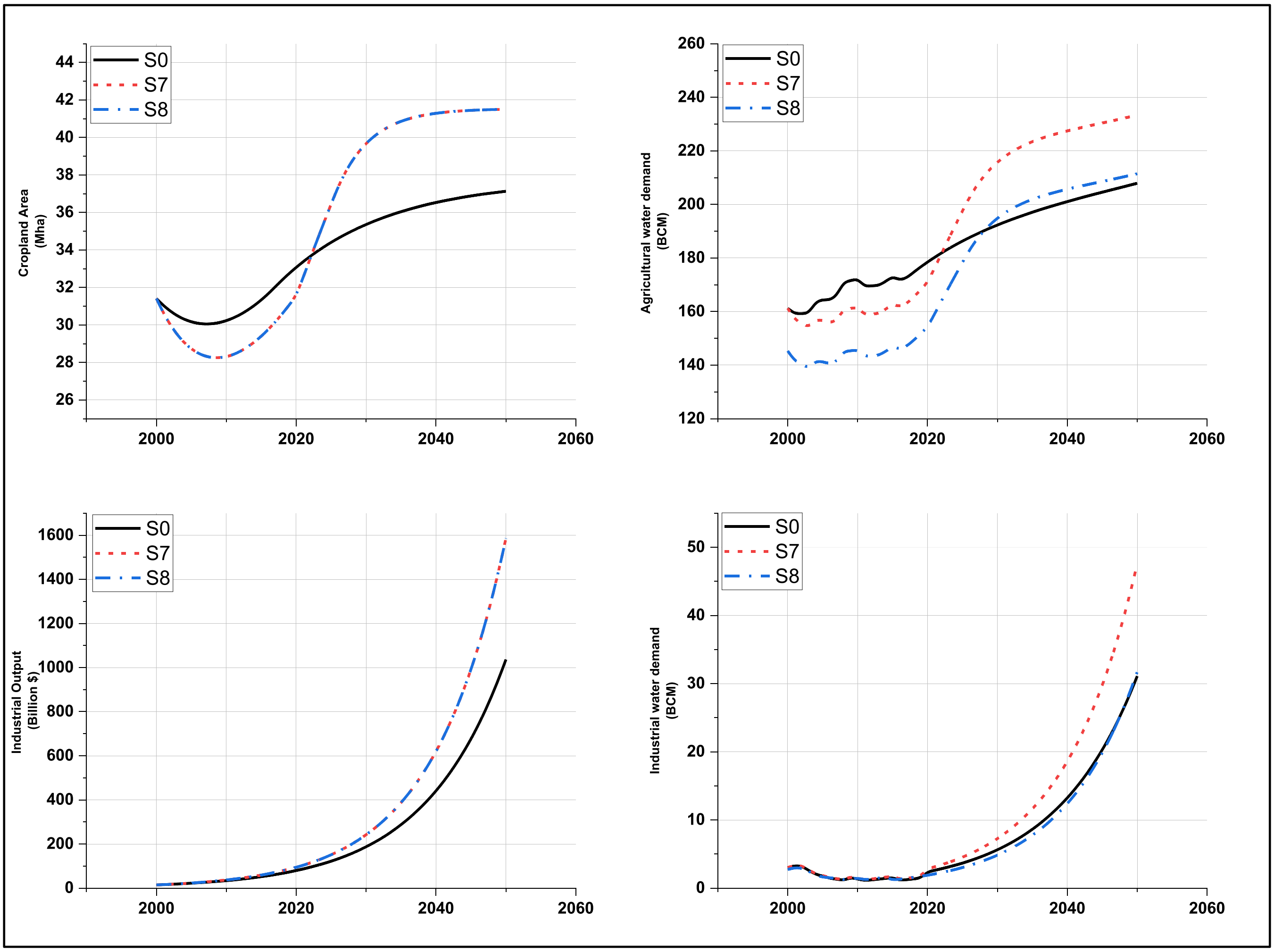

Fig. 8. Economic Development scenarios.

5. Discussion and conclusion

In conclusion, the system dynamics model developed in this study integrates critical variables including population, agriculture, livestock, industry, and water and demonstrates the intricate interactions and reciprocal influences among them. By capturing these relationships, the model offers valuable insights for evaluating policy options, supporting planning, and guiding decision-making on resource management and economic growth in Pakistan. The simulations highlight not only the consequences of different policy actions on water supply and demand but also the trade-offs and synergies that emerge across key sectors. These findings underscore the importance of a deeper understanding of intersectoral linkages and their implications for system-wide responses in order to design effective and resilient water management strategies. This study therefore establishes a foundation upon which future research can build by broadening the model's scope and refining its accuracy, ultimately providing a more comprehensive representation of the system to support evidence-based decision-making.

The research also yields five key insights into Pakistan's water management challenges and opportunities. First, the comprehensive scenario emerges as the most effective pathway, with the potential to accelerate economic growth, sustain an appropriate pace of development, and significantly narrow the gap between water supply and demand, thereby advancing the country toward more sustainable development.

Secondly, the study's findings indicate the profound and significant impact of the water demand side on the water supply and demand gap. The disparity between water supply and demand is subject to significant changes due to changes in several interacting subsystems, each of which has a major impact on water demand. By adjusting policies related to the demand side of water, it is possible to shorten these water discrepancies.

Thirdly, the study has shown that water needs will rise as the population grows and the economy expands. Restricting water consumption will not be an option for shortening the water supply and demand deficit in this situation. Therefore, the exploratation rate of water resources should be gradually increased to improve the water supply.

Fourthly, increased investment in water resources infrastructure is necessary for economic growth to promote the sustainable exploitation of water resources. The study highlights that the input-output ratio of agriculture and industry resources is greater in Pakistan and water losses during water transport are huge, thus to stimulate the economy and efficiently utilize water resources, the Pakistan government should enhance the input-output ratio of industry and focus more on water use efficiency.

Finally, the study has highlighted that any limitation in water supply by environmental factors and the Kashmir conflict poses a severe threat to Pakistan's economy. Exploration of alternative water resources and increase in current storage capacity through building new dams is crucial. This research provides a useful foundation for further studies to explore these issues in more depth and to support the development of

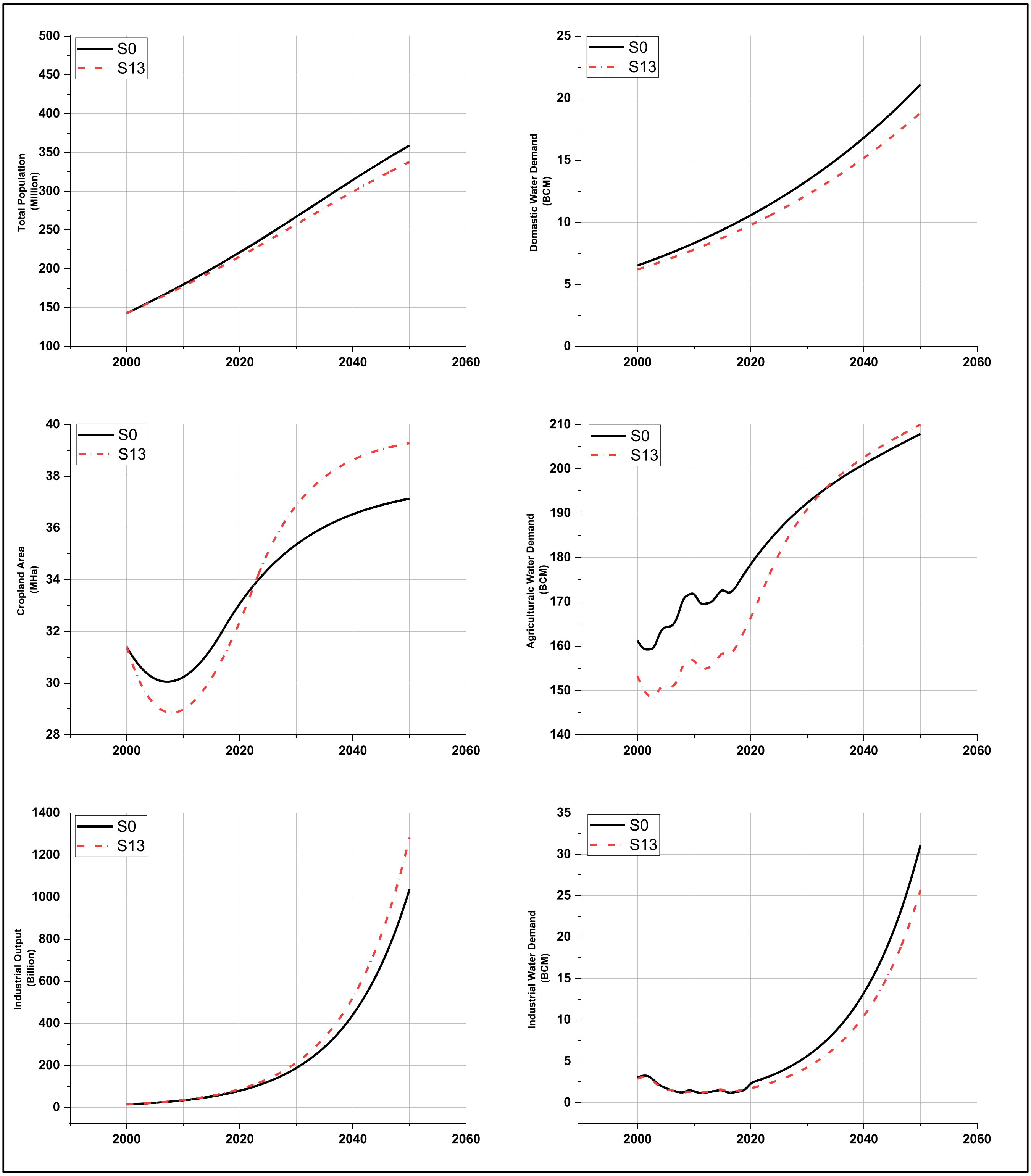

Fig. 9. Comprehensive scenario.

effective water resources management policies in Pakistan.

This study elucidates several pivotal findings and innovations. Most prominently, the comprehensive scenario assumes a distinctive role in harmonizing Pakistan's economic growth with water sustainability. The simulation demonstrated that this scenario could diminish the projected supply-demand gap by approximately 38% while concurrently enhancing GDP by 21% compared to the baseline. These outcomes underscore that integrated strategies combining demand-side measures, infrastructure investment, and policy reforms are more effective than isolated interventions.

A second innovation of this research lies in its national-scale integration of socio-economic and hydrological subsystems, an approach rarely attempted in earlier Pakistan-focused models. By explicitly capturing the feedback loops among population growth, industrial expansion, agricultural development, and water supply, the study provides a more realistic and nuanced understanding of long-term system dynamics.

The implications of these findings extend well beyond Pakistan. Many other arid and water-stressed countries, including Iran, Egypt, and several in Central Asia, face comparable challenges in balancing economic development with environmental sustainability. For these regions, the model presented here offers not only methodological lessons but also practical insights for policy formulation in contexts characterized by scarcity, governance limitations, and climate risk.

Comparative evidence from similar settings reinforces the relevance of our results. For example, Keyhanpour et al. [90] applied a system dynamics framework to Iran’s Khuzestan province using a water––food–energy nexus approach and concluded that only integrated strategies—linking demand management with efficiency improvements—could stabilize water use, echoing the outcomes of our comprehensive scenario. Likewise, Abdelkader [91] employed SDM for the Nile Basin in Egypt, finding that coordinated investment and cross-border cooperation were essential for sustainable resource use. In Central Asia, SDM applications to the Aral Sea Basin have shown that uncoordinated upstream withdrawals create persistent shortages downstream, again highlighting the necessity of cooperative and integrated approaches [92]. Collectively, these parallels demonstrate that the lessons drawn from Pakistan’s case resonate across other water-stressed contexts, enhancing the broader policy significance of our findings.

5.1. Policy suggestions

The study presents a comprehensive approach to address the challenges of water resources management. It proposes three types of policy suggestions with varying time frames, namely short-term (1-2 years), medium-term (2-5 years), and long-term (<5 years) to achieve water resources balance.

5.1.1. Population subsystem and water resources balancing policies

This study suggests that population growth has a direct and indirect impact on water resources, and that policies are needed to create a balance between population and water resources. In the short-term, effective community awareness and cost implementation can help reduce water resources' stress. In the medium-term, infrastructural improvements and wastewater treatment can increase water supply and reduce the threat to the ecosystem. In the long-term, a population policy that aims for sustainable growth over the long-term can help mitigate the impact of population expansion on the environment and natural resources. The study also suggests that restricting urbanization can relieve the water supply and demand gap stress.

5.1.2. Agriculture subsystem and water resources balancing policies

Simulation results of this study suggest that agricultural expansion puts pressure on water resources and increases the water shortage. In the short-term, knowledge transfer to farmers on water needs, crop-specific water requirements, and altered cropping patterns can help conserve water and address issues like waterlogging and salinity. In the medium term, lining of conveyance systems and modern irrigation technologies can increase water supply and enhance water use efficiency. In the long-term, a regulatory framework on groundwater abstraction is needed to monitor and prevent overuse and enhance and expand flood and drought forecasting techniques to prevent loss of life and property. Overall, the study suggests that a comprehensive approach is needed to manage water resources for agriculture, including improving knowledge transfer, adopting modern technologies, and regulating water use.

5.1.3. Industrial subsystem and water resources balancing policies

The industrial sector is highly reliant on groundwater and has a high water demand, which is expected to increase in the next three decades. Rapid growth in industrial sectors has led to over-exploitation of groundwater, resulting in groundwater decline, contamination, and land subsidence. To address this, the study proposes a policy of commercial licenses for sustainable management of water resources by restricting groundwater abstraction. In the medium-term, improving wastewater treatment and reusing this water can reduce water stress and improve the environment. In the long-term, Water-saving technologies can help industries expand while also allowing water supplies to improve over time. Providing subsidies for the adoption of these technologies is recommended as an incentive.

5.1.4. Water subsystem

This research indicates that increasing water supply is essential for sustainable water resources management in the present and the future, even though demand-restriction measures can provide short-term relief from water resource stress. Rainwater harvesting and artificial groundwater recharge are two technologies that can boost water availability and reduce water resource stress in the short term. In the medium term, building small storage reservoirs, current dam extension projects, and controlling evaporation loss can help conserve water resources and explore new fresh groundwater resources. In the long-term, constructing large storage reservoirs can further aid in sustainable water management by capturing and using water that is currently being wasted. The study also highlights the need for effective legislation and execution to control and price groundwater usage to limit over-extraction.

5.2. Limitations

Despite this study offers valuable insights, it is not without limitations. Firstly, data constraints necessitated the adoption of simplifying assumptions for certain variables, such as groundwater recharge rates and behavioral responses to policy interventions. Secondly, the model's structure was intentionally simplified to maintain tractability, which resulted in the exclusion of certain dimensions, including climate variability, detailed regional dynamics, and institutional implementation challenges. Thirdly, future uncertainties, such as sudden geopolitical disruptions or rapid technological advancements, were only partially represented. Consequently, although the model provides a reliable overview of long-term system dynamics, its projections should be interpreted with these limitations in mind. The model contains a relatively low number of variables and equations; hence, the model's scope appears limited to several factors and insufficient to represent all factors at the national level. These points serve to suggest directions for future research.

Future research should prioritize the enhancement of the model by integrating more detailed regional data, incorporating climate variability scenarios consistent with IPCC projections, and combining species distribution models (SDM) with agent-based components to effectively capture micro-level behavioral responses. Additionally, the inclusion of factors such as water quality, energy consumption, and ecosystem services could further augment the model's comprehensiveness.

Beyond its academic applications, this model holds substantial practical implications. Policymakers and water authorities, such as IRSA and WAPDA, can utilize it as a decision-support tool to evaluate policy interventions prior to their implementation. Urban planners may employ scenario outputs to ensure that urban expansion aligns with sustainable water availability. Furthermore, Ministries of Finance and Planning could leverage the results to substantiate investments in infrastructure such as dams, canals, or wastewater recycling systems. International development partners might also apply the insights to direct funding toward interventions with the greatest systemic impact. Consequently, the model serves not only as a source of analytical insights but also as a pragmatic planning tool for stakeholders in real-world contexts.

CRediT authorship contribution statement

Ahmad Raza: Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Muhammad Bilal:** Writing – review & editing, Resources, Data curation. **Sohaib Aqib:** Writing – review & editing, Visualization. **Ali Raza:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Appendix A

Table A.1
Stages of water scarcity.

Water scarcity	Volume of water available (m3/person/year)
Beyond the barrier	<500
Water scarcity	500 – 1,000
Water stress	1,000 – 1,700

Table A.2
Initial parameter values of selected variables.

Variables	Values	Unit	Source
Rural population birth rate	31	per 1,000 people	[93]
Urban population birth rate	16	per 1,000 people	[93]
Urbanization rate	1.02	%	[48]
Per capita food consumption	413.8	kg/year	[94]
Average crop yield	2200	kg/ per ha	[95]
Cropland area	31.41	million hectares	[77]
Maximum Arable land	37.76	million hectares	[77]
Exploitation delay	15	years	Assumption
Livestock growth rate	4.3	%	[48]
Total Livestock	119	million livestock	[48]
Industry Output	14.392	million USD	[96]
Industry Output growth rate	8.12	%	[96]
Eastern Rivers flow	5.055	BCM	[79]
Western Rivers flow	165.2	BCM	[79]
Kabul river flow	21.5	BCM	[79]
Participation	78.8	BCM	[80]
Irrigation return water	35.05	BCM	[80]

Table A.3
Scenario simulations.

Parameter	Business as usual	Population growth scenario		Agriculture growth scenario		Industry growth scenario		Economic Development		Dry Conditions		Kashmir Conflict Expedition	Structural Improvements	Comprehensive Scenario
	S0	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**	**S13**
Population growth rate	Constant	Increase by 10%	Decrease by 10%	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Decrease by 5%
Urbanization rate	Constant	Increase by 10%	Decrease by 10%	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Decrease by 5%
Crop yield	Constant	Constant	Constant	Increase by 10%	Increase by 10%	Constant	Constant	Increase by 10%	Increase by 10%	Constant	Constant	Constant	Constant	Increase by 5%
Exploitation delay	Constant	Constant	Constant	10-year decrease	10-year decrease	Constant	Constant	10-year decrease	10-year decrease	Constant	Constant	Constant	Constant	5-year decrease
Agricultural land area	Constant	Constant	Constant	Increase by 10%	Increase by 10%	Constant	Constant	Increase by 10%	Increase by 10%	Constant	Decreased by 10%	Constant	Constant	Increase by 5%
Livestock growth rate	Constant	Constant	Constant	Increase by 10%	Increase by 10%	Constant	Constant	Increase by 10%	Increase by 10%	Constant	Constant	Constant	Constant	Increase by 5%
Industrial growth rate	Constant	Constant	Constant	Constant	Constant	Increase by 10%	Increase by 10%	Increase by 10%	Increase by 10%	Constant	Constant	Constant	Constant	Increase by 5%
Precipitation	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Decrease by 40%	Decrease by 40%	Constant	Constant	Increase by 5%
Surface water	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	Constant	western river flow decrease by 50%	Storage capacity increase by 50%	Storage capacity increase by 25%
Water consumption (Domestic, Agri, Industry)	Constant	Constant	Constant	Constant	Decrease by 10%	Constant	Decrease by 10%	Constant	Decrease by 10%	Constant	Constant	Constant	Constant	Decrease by 5%

Table A.4
Error rate and coefficient of determination between the true and simulation values.

Error rate					
Year	Rural population	Urban population	Cropland Area	Agricultural water demand	Industrial output
2000	0.00%	-1.74%	-0.91%	3.21%	0.00%
2005	-2.23%	-1.27%	-2.60%	-3.93%	-7.71%
2010	-1.97%	-0.62%	-0.06%	-4.91%	-3.09%
2015	-0.97%	0.34%	0.43%	-1.11%	0.53%
2017	-0.49%	0.70%	0.09%	1.32%	0.36%
Coefficient of determination					
2000-2017	1	1	0.91	0.85	0.96
Discrepancy coefficients					
2000-2017	0.16	0.28	0.43	0.39	0.56

Table A.5
Simulation forecast and growth rate.

Variables	2000	2010	2020	2030	2040	2050	Growth Rate % (2000 -2050)
Total population (Million)	142.34	179.74	221.28	267.16	314.53	358.93	152.16
Cropland area (Mha)	31.41	30.22	33.07	35.36	36.53	37.13	18.21
Livestock (Million)	119.00	170.02	242.92	347.07	495.87	708.48	495.36
Industrial output (Billion USD)	14.39	33.86	79.64	187.35	440.70	1,036.68	7,102.78
Domestic water demand (BCM)	6.51	8.32	10.56	13.35	16.81	21.09	223.87
Agricultural water demand (BCM)	161.24	172.30	178.47	192.32	201.05	207.89	28.93
Industrial water demand (BCM)	3.02	1.35	2.39	5.62	13.22	31.10	928.97
Water resources supply (BCM)	227.02	227.02	222.76	211.56	202.35	191.03	(15.85)
Water Shortage (BCM)	27.55	38.74	52.45	83.52	112.52	152.84	454.87

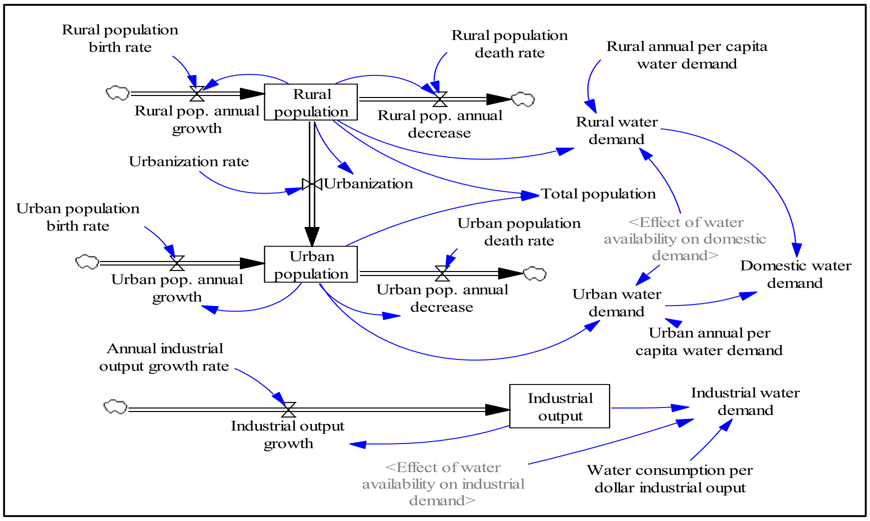

Fig. A.1. SFD- Population & industry subsystems.

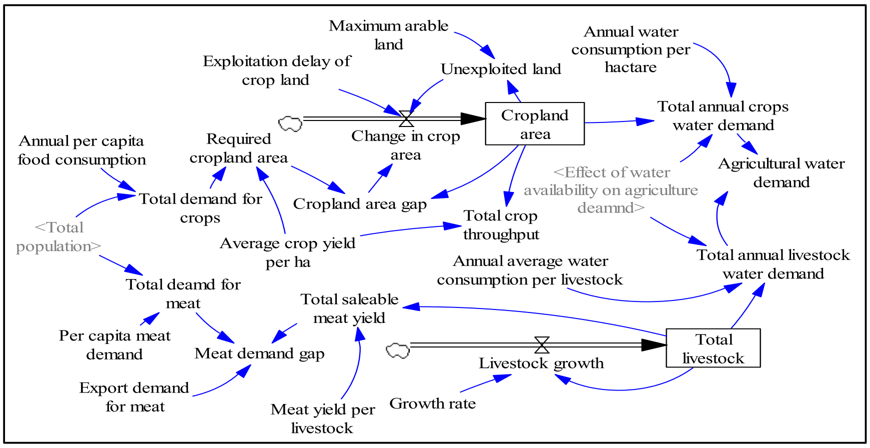

Fig. A.2. SFD- Agriculture subsystem.

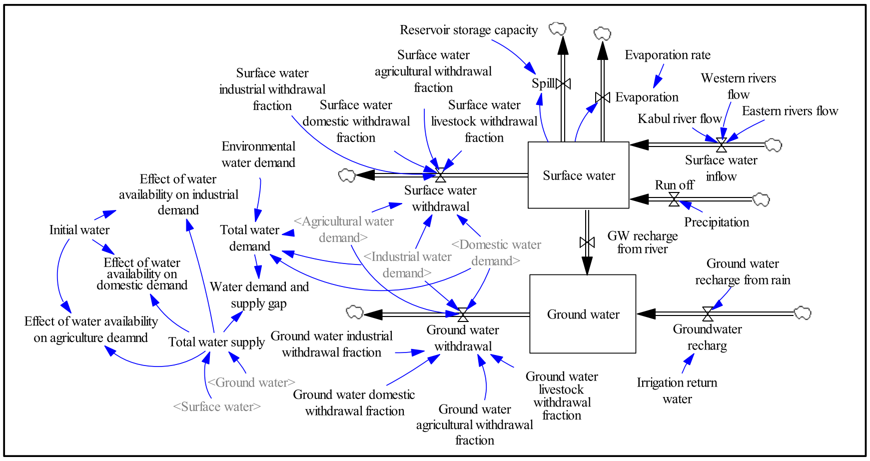

Fig. A.3. SFD- Water subsystem.

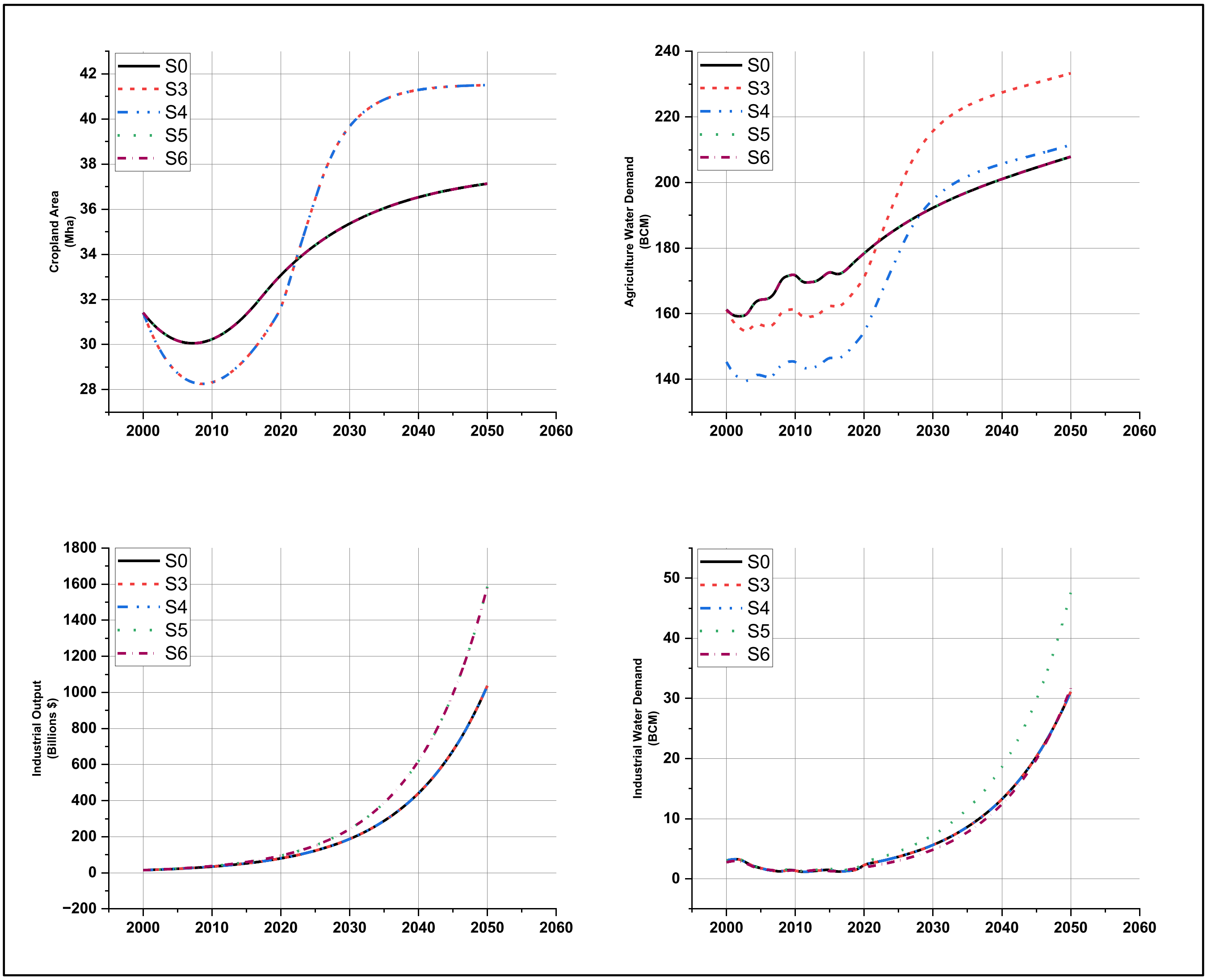

Fig. A.4. Agriculture and Industry growth scenario.

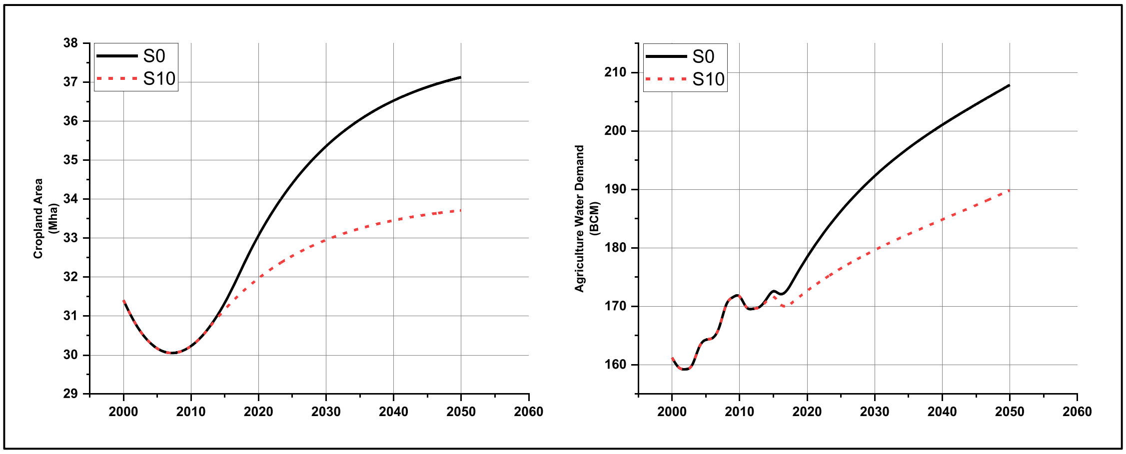

Fig. A.5. Impact of Drought on cropland area.

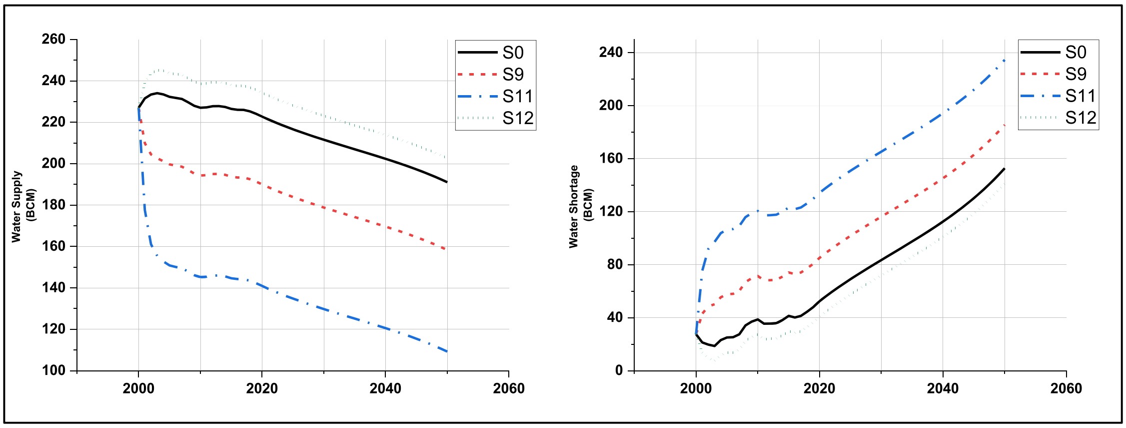

Fig. A.6. Dry conditions, Kashmir conflict, and infrastructure development.

Data availability

Data will be made available on request.

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