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RESEARCH ARTICLE

Water and Future Markets in Pakistan: A Dynamic CGE-Water Framework

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ABSTRACT

The demand for freshwater is growing rapidly in Pakistan due to rising agricultural cultivation and its intensification. In addition, the fast-growing population in the country (almost 2% per annum) and industrial growth are also adding to the rising water demand in the country. This study specifically delves into how the rapid increasing population affect the water prices in Pakistan and discusses the resulting structural changes in the economy where the water supply remains the same. The simulation results of our dynamic CGE model reveal an 11% rise in water prices by 2040, influencing agricultural costs and diminishing outputs, notably in staple crops like rice and wheat. The burgeoning populace introduces surplus labor, impacting real wages and triggering a structural transformation in production, evidenced by declining agricultural sectors but a rise in meat and industrial production. Altering dietary patterns are anticipated, favoring meat over cereals. Trade dynamics exhibit declines in staple crop exports but significant rises in fishing and service sector exports. Escalating water costs drive up imports of water-intensive crops, aggravating strain on the agricultural sector. Despite an improved trade balance, the welfare loss of population growth exceeds $2 billion, signifying a need for urgent intervention.

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1. Introduction

The subcontinent, particularly Pakistan, heavily relies on irrigation water from both man-made and natural sources to meet the demands of its agricultural sector. Unfortunately, there has been a concerning trend of acute water shortages in recent years. In 2010, the per capita water availability was approximately 1,040 cubic meters, a figure expected to plummet to around 500 cubic meters by 2035 [1]. The looming water crisis is characterized by insufficient potable and unpolluted water to meet the region's demand, exacerbated by climate change, including droughts and floods, pollution, overuse of water, population growth, and intensive agricultural water use[2–5]. Additionally, the replenishment of underground water sources is hindered by human, agricultural, and industrial wastes [6].

According to the Falkenmark Water Stress Indicator outlined in a climate change report in 2001, a country or region is deemed to be under "water stress" when annual water supplies fall below 1,700 cubic meters per person. Below 1,000 cubic meters per person, a country faces water scarcity, with periodic or limited water shortages expected between 1,700 and 1,000 cubic meters per person per year.

Previously, a few studies employ either a global dataset to understand the water scarcity issue[7–10] while others use single country analysis [11–13]. A part of literature focuses on sectoral/regional aspects[2, 14–16]. It is nevertheless stated that all these existing studies highlight different important aspects of water scarcity (**Table 1**).

Pakistan's current water storage capacity is less than ten percent, approximately 13.7 million acre-feet (MAF), of the total annual water received (about 145 MAF)[1]. Despite having the largest irrigation system of canals requiring 40 MAF annually, the absence of new dams results in the wastage of 29 MAF of water. This critical situation indicates that Pakistan is rapidly depleting its fresh water resources, and the country is projected to face a significant irrigation water shortage of 31 MAF by 2025, posing a severe threat to its agriculture-based economy.

Despite being a major user of water, the agriculture sector plays a crucial role in Pakistan, contributing over 19 percent to the country's Gross Domestic Product (GDP) (Economic Survey of Pakistan, 2019–2020). The sector is a significant exporter of raw materials such as cotton and rice, as well as finished products like milk packs, clothing, and jackets. The dependence on agriculture is pivotal for sustainable trade, job creation, economic growth, and the generation of foreign reserves. Water shortages directly and indirectly harm the agricultural sector and other facets of the country's economy.

This research endeavors to shed light on the impending irrigation water market in future and its potential impact on Pakistan's economy. Anticipated repercussions include a temporary increase in the price of agricultural land and a permanent rise in the market price of irrigation water. The shortage directly affects the production of various crops, leading to a reduction in overall crop production. The investigation employs a dynamic Computable General Equilibrium (CGE)-water framework, a unique approach that integrates the static GTAP-Water model (Global Trade Analysis Project) with the dynamic GTAP-Energy model [18, 19]. This multi-region, multi-sector, recursively dynamic general equilibrium framework provides a comprehensive understanding of the complex interplay between water scarcity and economic dynamics, addressing key research questions not previously explored.

The rest of the study is as follows: Section 2 discusses major studies, and their research findings therein gaps, and modeling frameworks used. Section 3 discusses the economic and econometric models of the present study. Section 4 discusses the course of simulation analysis. Section 5 presents the simulation results of different scenarios employed. Section 6, finally, concludes the research findings.

2. Literature Review

This section highlights the mainstream modeling frameworks employed in literature. Notwithstanding, the current literature review will help us to develop our modeling framework and to design our simulation design.

Specifically, a few studies employ a global dataset to understand the water scarcity issue[7–10] while others use single country analysis [11–13]. Some literature focuses on sectoral or regional aspects[2, 14–16]. It is nevertheless stated that all these existing studies highlight different important aspects of water scarcity (**Table 1**).

Many of the studies link the water scarcity with agriculture in one way or the other. Chen et al. [16] suggest that water scarcity may be tackled by improving local agricultural practices. Likely, Zou et al. [17], among others state that water management for increasing efficiency may help reduce the greenhouse gas emissions, thereby helping to reduce the adverse impact of climate change. Using the CGE modeling framework, a few studies assess the issue of water scarcity and the role of agricultural adaptations to mitigate the effects of pollution and water stress in different regions/countries[13, 14, 20]. These studies provide novel findings in the regions selected to conserve the rare water resources via different policy options. The present study also attempts to cover the gap in the literature regarding Pakistan, considering the paucity of literature on the issue for this region.

a) Similarities:

Time Period: The studies cover various time periods ranging from the 1960s to 2014, providing a historical perspective on water-related issues.

Geographical Focus: The studies examine water-related issues in specific countries (e.g., USA, China, India, Israel, Italy, Spain, Tunisia, Bangladesh, Iran) as well as globally, offering insights into both local and global contexts.

Models and Methodologies: Different studies employ various models and methodologies to analyze water-related issues, including WaterGAP3 Model, Multi-regional Input-output Model, Water-Footprint Analysis, CGE Model, Multinomial Logit Regression, and various simulation models.

b) Differences:

Scope and Scale: The studies vary in scope, with some focusing on specific regions or countries (e.g., Willamette River Basin, USA) and others taking a global perspective. The scale of analysis also differs, ranging from specific river basins to worldwide assessments[21].

Factors Examined: While all studies address water-related issues, the specific factors considered vary. For instance, some studies focus on irrigation productivity[15], water withdrawals and trade[16], water scarcity in cities[8], and the impact of climate change on water shortage[22].

Findings: The results and conclusions of the studies differ based on their focus and methodologies. Some highlight the role of technology in improving irrigation productivity[15], while others emphasize the impact of trade on water use[16] or the importance of water charging policies[13].

In summary, while there are commonalities in the temporal focus, global concern for water scarcity, and the use of advanced modeling techniques, the differences lie in the specific geographical, methodological, and contextual nuances addressed by each study, reflecting the complexity and multifaceted nature of water-use challenges.

3. Methodology

The GTAP model is the most sophisticated CGE framework, meticulously crafted to assess the economic repercussions of trade policies and other transformative events[36]. Underpinning the model lies the fundamental principle of interconnected markets, acknowledging that any alteration in one market will inevitably trigger cascading effects throughout the entire economic structure. It is instrumental in investigating a diverse array of critical issues, including trade liberalization in developing nations, environmental policies, and inclusive growth policies.

The dynamic GTAP model emerges as an extension of its static counterpart, enabling the analysis of economic impacts across time[19]. This enhanced model empowers users to simulate the intricate interplay between trade policy shifts, technological advancements,

Table 1. Reviews of Literature.

S. No.	Author(s)	Time Period	Country/Region	Methodology	Results
1	Njuki and Bravo-Ureta, 2019 [15]	1960–2004	48 States of USA	Single-factor Approach	Irrigation productivity increased modestly in various states, driven by technological progress.
2	Chen et al. 2018 [16]	2012	188 Regions Worldwide	Multi-regional Input-output Model	Around one-third of water withdrawal is linked to interregional trade. Improving the local agricultural practices can save water.
3	Florke, Schneider, McDonald, 2018 [8]	1971–2000	World	WaterGAP3 Model	Nearly 19% of cities, relying on surface-water transfers, might face potential conflict between the urban cities and agricultural sectors.
4	Shtull-Trauring and Bernstein, 2018 [12]	2007–2012	Israel	Water-Footprint Analysis	Around 25% of total Blue (irrigation) water used for agriculture production is exported.
5	Jaeger et al., 2017 [11]	2010	USA	Willamette River Basin Model	Key factors behind water scarcity are high cost of transportation, limited storage capacity, and opportunity cost of water.
6	Liu et al. 2017 [9]	2006	World	SIMPLE-G and Water Balance Models	Rising factor productivity in irrigated sectors is expected to boost irrigation water demand while irrigation vulnerability might decrease by inter-basin water transfers.
7	Brauman et a., 2016 [7]	1971–2000	worldwide	WaterGAP3 Model	At least, around 71% of world irrigated area is experiencing periodic water shortage.
8	Perez-Blanco et al., 2016 [13]	2011	Italy	CGE Model	Water charging policy is effective as long as water charges remains under 55 Eurocents$\cdot$m^{-3}.
9	Alam, 2015 [2]	2013	546 farming households in Bangladesh	Multinomial Logit Regression	Awareness about adverse effects of climatic change is more likely to lead farmers to adaptation strategies.
10	Esteve et al., 2015 [23]	2011	Spain	WEAP Model	Lack of technology is a major factor for inefficient water use by farmers along with decisions made by neighboring farmers.
11	Chouchane et al., 2015 [24]	2005–2011	Tunisia	Water Footprint Assessment	The country is facing severe water scarcity as total blue water used in crop production is around 31% of total renewable blue water.
12	Samian et al., 2015 [25]	148 Farmers, in year 2011	Iran	Factor Analysis Method	Technical, institutional, economic and social factors are mainly responsible for water shortage.
13	Medellín-Azuara et al., 2015 [26]	2012–2014	USA	SWAP & C2VISim Models	Reduced access to groundwater, and uncertain delivery of surface-water during drought reduced crop revenues in the country.
14	Fishman, Devineni, and Raman, 2015 [27]	1901–2004	India	Sequent Peak Algorithm	Adoption of technologies such as drip and sprinkler irrigation can reduce the extraction of groundwater by two thirds.
15	Fishman et al., 2015 [17]	2010	China	Water-Saving Irrigation Method	Improved water use efficiency can effectively reduce greenhouse gas emissions.

Table 1. *Cont.*

S. No.	Author(s)	Time Period	Country/Region	Methodology	Results
16	Chatuverdi et al., 2015 [10]	2005	World	GCAM Model	Agrarian regions particularly China and India are expected to experience rising water demands over the next century.
17	Marshall et al., 2015 [22]	2001–2008	USA	CGCM, CSIROMK and MIROC Models	Irrigation water shortage linked to climate change shows different effects on cropland use.
18	Taheripour et al., 2015 [28]	2007	India	CGE Model	Due to water shortage, the welfare losses are expected to increase by $3.2 billion in 2030.
19	Zhou, Wu, and Zhang, 2015 [29]	2000–2009	China	OLS	Price mechanism, legally enforceable water rights, and water quotas create incentives for water conservation and improved irrigation efficiency.
20	Koopman et al., 2015 [14]	2001	87 Regions	GTAP-W	There is considerable room for adaptation measures given that total agricultural losses are much lower than the nonagricultural losses.
21	Walmsley, Dimaranan, and McDougall, 2000 [30]	2000	World	dynamic GTAP model	The study focuses on modeling global trade dynamics and provides valuable insights into the economic interactions among countries/regions.
22	Yu et al., 2013 [31]	2013	Pakistan	integrated systems framework	The study emphasizes the need for strategic prioritization, improved planning, and management of resources to address the challenges posed by climate risks in the Indus Basin.
23	Young et al., 2019 [32]	2023	Pakistan	different methods	The report highlights complex water issues, challenges that may hinder progress in economic and human development, unmitigated water-related risks, and opportunities for economic growth and poverty reduction. It also analyzes the relationship between water sector performance and broader economic, social, and environmental outcomes.
24	Kirby and Ahmad, 2022 [33]	2022	Pakistan	integrated population –GDP–food–water model	Different scenarios, such as higher population growth or lower rates of yield increase, may worsen water security, while others may improve it.
25	Davies and Young, 2021 [34]	2021	Pakistan	CGE model	water demand could exceed supply by 2055. However, with appropriate investments and reforms, water scarcity may not prevent Pakistan from ensuring food security and reaching upper-middle income status by 2050.
26	Nguyen et al., 2023 [35]	2024	Globa South	snow ball sampling review	Rural land use should be geared towards the promotion of resource and biodiversity conservation, development of agroforestry and tree-based farming systems, diversification of crops, and utilization of climate-resilient cultivars and neglected and under-utilized plants.
27	Briand et al., 2023 [21]	2023	South Africa	CGE water model	CGE model predicts a decrease of South African GDP by −0.44% in 2030. The long-term impact of water scarcity varies from one sector to another, the most negatively impacted sectors being those related to water. Due to water scarcity, unemployment will increase in the short term by 0.76%

Note: Blue water represents the primary source of natural water supply (such as groundwater and surface water runoff) while green water is the water from rainfalls.

demographic changes, and other influential factors, illuminating their combined impact on the trajectory of economies over time. The dynamic structure proves to be an invaluable tool for policymakers and researchers alike, fostering a deeper understanding of the long-term economic implications associated with various policy options.

The present study develops a dynamic CGE water (Gdyn-W) framework, which is a multi-region, multi-sector, recursively dynamic framework. Basically, it links the static GTAP-Water model along with the dynamic GTAP-Energy model [18,19]. The main characteristic that distinguishes the dynamic GTAP model from other classes of dynamic CGE models is its disequilibrium approach to portray the capital mobility. It maintains the short-term and medium-term dissimilarities in the rates of return, which can, however, be abolished in the long term. Hence, this practice allows for imperfect capital movement between different regions in the short term to the medium run while allowing for perfect capital mobility in the long term.

The new production structure in Gdyn-W model enables substitution likelihoods between irrigation water and other key factors of production, whereas which is missing in the standard GTAP model [18]. Hence, it allows substitution likelihood between irrigation water and irrigable land using a nested CES function at a lower level, which represent the first nest. The demand for irrigation water (Wtr) along with irrigable land (Lnd) becomes (a detailed list of model variables and parameters is provided in the **List A1** and **List A2**):

$$qfe_{i,j,r} = -afe_{i,j,r} + qlw_{j,r} - ELLW_{j,r} * [pfe_{i,j,r} - afe_{i,j,r} - plw_{j,r}] \quad (1)$$

$$i = Lnd, Wtr$$

Where the unit cost of the irrigable land-water composite is:

$$plw_{j,r} = \sum_{k \in ENDWLW} SLW_{k,j,r} * (pfe_{k,j,r} - afe_{k,j,r}) \quad (2)$$

4. Simulation Design and Database

The demand for water is growing rapidly over time in Pakistan due to rising agricultural cultivation and its intensification. In addition, the fast-growing population (almost 2% per annum) in Pakistan and industrial growth are also adding to the rising water demand in the country. If suitable policy measures are not taken in time, it is expected to cause huge welfare losses through household choices about food decisions, structural changes in the economy through changes in production patterns and international trade. Hence, this paper simulates how the economy of Pakistan is affected by this rapid increase in population with the water supply remaining the same.

All these changes are incorporated to the most recent GTAP database version 11, which is a publicly available database (https://www.gtap.agecon.purdue.edu/-databases/v11/)). It comprises bilateral trade statistics, transport and protection data. Originally, it comprises 65 sectors for 141 countries (regions) worldwide, representing 98% of the global GDP (See **Table A1**). Since it provides a good representation of the global economy, it is utilized by the contemporary applied general equilibrium analysis globally.

5. Results

This scenario incorporates the increase in population with no change in total water availability. The baseline year of the GTAP database is 2017, in the recursive dynamic setting, where decisions are made sequentially over time, taking into account the evolving state of the economy. In our dynamic CGE, on the other hand, are sophisticated economic models used to analyze how changes in one part of an economy can impact other parts, considering the interactions among various sectors, households, and markets. These models incorporate dynamic elements, allowing for changes over time.

Now, when these two are combined, a dynamic CGE model that employs a recursive dynamic setting is created. This model not only captures the intricate interdependencies between different economic agents but also factors in the evolving nature of the economy over time. It essentially models how economic decisions made at different points in time influence each other in a dynamic, changing economic environment.

With the given increase in population, the water price is expected to rise continuously in Pakistan, with a cumulative increase in the price of water around 11% in 2040 (**Figure 1**). The rising population stock provides more skilled and unskilled labor to the labor market, reducing the real wages in the labor market along with the prices of other factors. It is interesting to note that the price of Rainfed land is expected to reduce while the price of other land (to use groundwater infrastructure) is expected to rise in future due to change in climatic conditions in future.

Initially the output of rice, wheat, other cereal, and key crops (rice, wheat, cereal crops, vegetable and fruits, sugarcane, and other agricultural products) is unable to meet the required increase in demand emerging from the rising population. The output of the agriculture industry is expected to decrease in future. Similarly, the breeding of animals, processed food, the fishing and services industries also face a declining trend (**Figure 2**).

On the other hand, there is a structural change in the economy, and we observe a rise in meat production, and industrial production. Livestock, a subset of Pakistan's agriculture, accounts for roughly 56% of the value added in agriculture and contributes to nearly 11% of the country's GDP[37]. Hence, we expect a change in food pattern among people since the future cereal crop production will decrease and the meat production will rise. It is anticipated that the livestock capital of the country will decrease at a faster rate in future.

The structural changes in the economy through production also reflect in the trading pattern. The exports of rice, wheat, other cereal, and key crops are expected to reduce, while the exports of animals (products), meat, forestry, fishing, industry and services sectors are expected to increase (**Figure 3**). The highest rise in exports is witnessed in the fishing industry, which is expected to rise more than eight percent in 2040. Unlike land-based agriculture, fishing can tap into vast marine resources. Properly managed, these resources can sustain higher yields without immediate constraints posed by land availability.

Imports of rice, wheat and sugarcane increase the most because these crops are the largest consumer of agricultural water in Pakistan and the rising crop water makes the production of these crops expensive; whereas the imports of other crops increase moderately (**Figure 4**). Moreover, the country increases its reliance on the imported processed foods. In contrast, the imports of animals, meat, industry and other sectors reduce. Overall, the trade balance of the country improves by more than US$1.2 billion in 2040, but the welfare loss arising from the higher price of water, structural changes in the production and loss to real wages due to the rapid increase in population is more than US$2 billion (**Figure 5**). Hence, the cumulative losses arising from the rapidly increasing population costs Pakistan around 0.8% of GDP in 2040 (**Figure 6**) if the necessary measures are not takes into consideration to entertain this rising youth bulge.

6. Discussion and Analysis

The simulation results reveal several significant impacts of population growth on Pakistan's economy, particularly in relation to water scarcity and sectoral shifts:

6.1. Water Pricing and Factor Markets

The projected 11% increase in water prices by 2040 highlights the growing scarcity of water resources relative to population growth. This price surge is likely to have far-reaching effects across various sectors of the economy, particularly agriculture. The downward pressure on real wages due to increased labor supply suggests potential challenges in labor market absorption and income distribution.

6.2. Agricultural Sector Transformation

The decline in output of staple crops like rice, wheat, and other cereals, juxtaposed with an increase in meat production, indicates a significant structural shift in Pakistan's agricultural sector. This transformation may be driven by changing dietary patterns, relative factor prices, and the water-intensity of different agricultural activities. The reduction in cereal crop production raises concerns about food security and the country's ability to meet domestic demand for staple foods.

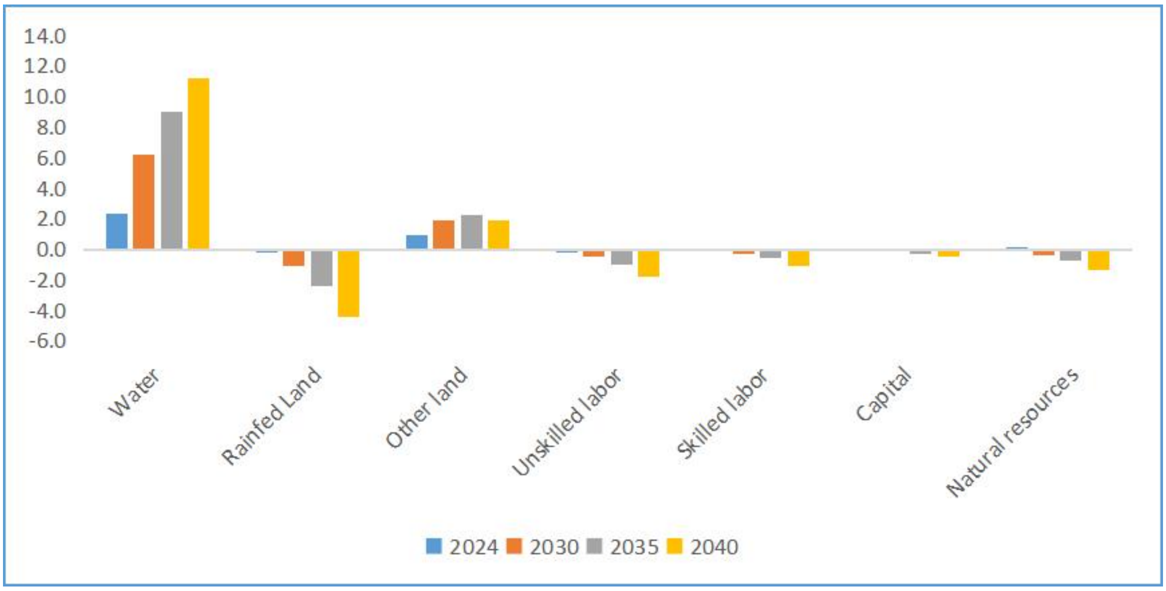

Figure 1. Change in factor prices (% change from baseline). Source: Authors' calculations. Note: Overall, the scientific justification lies in the basic principles of supply and demand along with the ability of the dynamic CGE model to capture the complex interactions between population growth, resource scarcity, and economic factors. It's important to note that this is a model-based prediction, and real-world outcomes might differ depending on various factors not explicitly included in the model.

6.3. Industrial and Service Sector Growth

The observed increase in industrial production and certain service sectors suggests a gradual economic transition from agriculture to more urban-centric activities. This shift aligns with typical patterns of economic development but may pose challenges in terms of rural-urban migration and the need for skill development in the workforce.

6.4. Trade Pattern Alterations

The projected decline in exports of water-intensive crops and the increase in their imports reflect the impact of rising water prices on comparative advantage. The significant growth in fishing exports presents an interesting opportunity, potentially driven by relatively lower water constraints in this sector. However, the overall shift in trade patterns may have implications for food security, foreign exchange earnings, and the balance of trade.

6.5. Welfare and GDP Impacts

The estimated welfare loss of over $2 billion and the GDP growth reduction of 0.8% by 2040 underscore the substantial economic costs associated with population growth under water scarcity conditions. These figures suggest that the positive effects of demographic dividends may be outweighed by resource constraints, particularly in water-dependent sectors.

6.6. Livestock Sector Dynamics

The projected faster reduction in livestock capital, coupled with increased meat production, suggests a shift towards more intensive livestock farming practices. This trend may have implications for rural livelihoods, land use patterns, and environmental sustainability.

6.7. Regional Water Management

The differential impact on rainfed land prices versus other land prices (for groundwater infrastructure) points to the complex interplay between climate conditions, water sources, and agricultural practices. This divergence may lead to regional disparities in agricultural development and water resource management challenges.

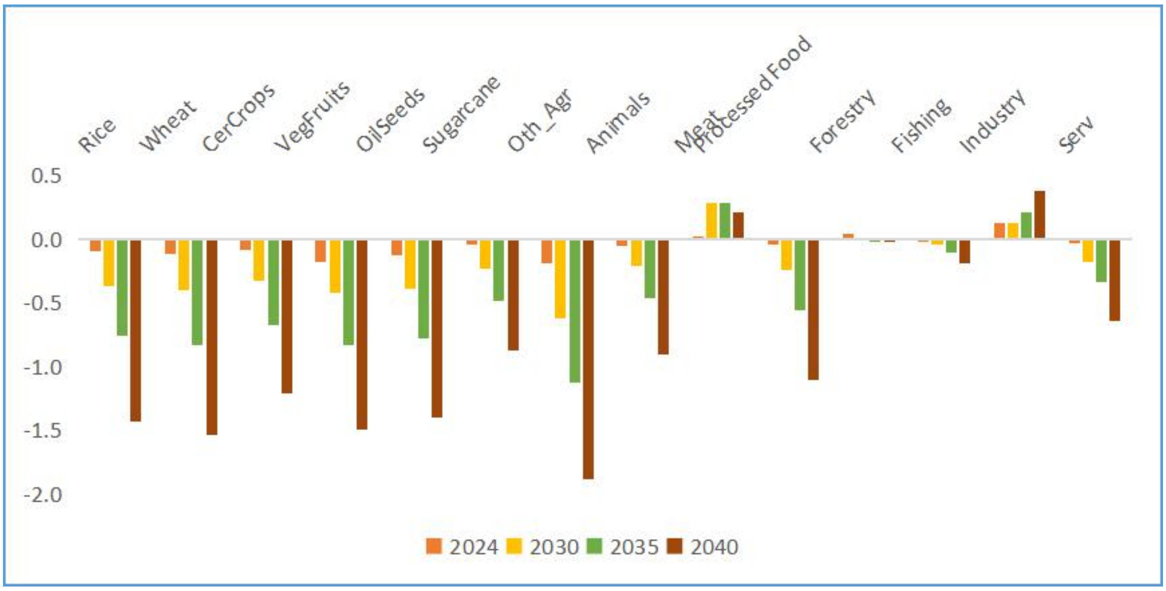

Figure 2. Change in sector output (% change from baseline). Source: Authors' calculations.

6.8. Food Security and Dietary Shifts

The projected changes in agricultural output and trade patterns suggest a potential shift in dietary habits, with a move towards more meat consumption and reliance on imported cereals. This transition raises questions about nutritional outcomes, food affordability, and the resilience of Pakistan's food system.

6.9. Economic Structural Transformation

The overall results indicate a significant structural transformation of Pakistan's economy driven by population growth and water scarcity. This transformation involves shifts from traditional agriculture to more water-efficient and higher-value sectors, potentially accelerating urbanization and industrialization processes.

In conclusion, the simulation results paint a complex picture of Pakistan's economic future under conditions of population growth and water scarcity. While some sectors show potential for growth and adaptation, the overall welfare and GDP impacts suggest significant challenges ahead. The findings underscore the need for comprehensive policies addressing water resource management, agricultural transformation, industrial development, and human capital formation to navigate these impending changes effectively.

7. Conclusions

The given scenario paints a comprehensive picture of Pakistan's evolving economic landscape, forecasting various shifts in its industries, agricultural outputs, trade dynamics, and the impending challenges due to the burgeoning population. Firstly, the looming increase in population appears to be a pivotal factor shaping Pakistan's economic trajectory. The projected rise in population is anticipated to instigate a continuous surge in water prices, estimated to elevate by approximately 11% by 2040. This upward trajectory in water prices stems from the escalating demand attributable to the expanding populace. Consequently, this surge in water costs is anticipated to inflict substantial welfare losses, highlighting a critical concern demanding immediate attention.

Furthermore, the correlation between population growth and its impact on the labor market is evident. The burgeoning population introduces a surplus of skilled and unskilled labor, thereby exerting downward pressure on real wages within the labor market. Additionally, this population surge leads to a decrease in agricultural output, especially in staple crops such as rice, wheat, and cereal crops, which are unable to match the escalating demand arising from the burgeoning populace.

The analysis also sheds light on the evolving dynamics within the agricultural sector, indicating a structural

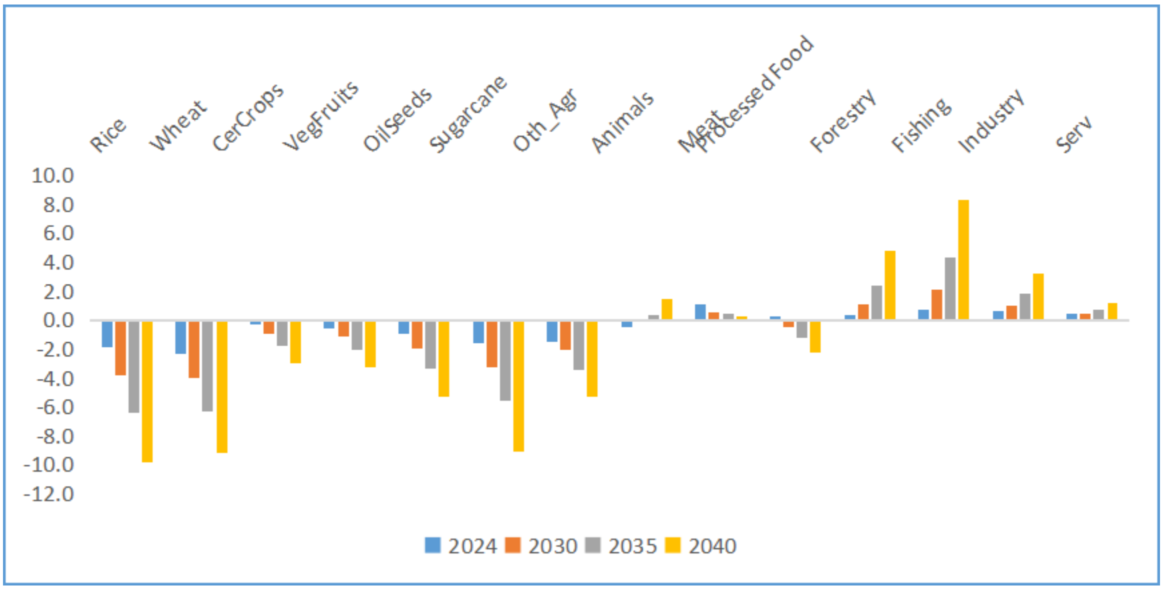

Figure 3. Change in exports (% change from baseline). Source: Authors' calculations.

transformation. Notably, while the output of certain agricultural segments faces decline, there is a notable rise in meat production, signifying a shift in the country's food consumption patterns. This shift is largely attributed to the foreseen decrease in cereal crop production and the concurrent rise in meat production, altering the dietary preferences of the populace.

Moreover, this shift in production dynamics also manifests in Pakistan's trading patterns. The prognosis indicates a decline in exports of staple crops like rice, wheat, and other cereals, accompanied by a notable surge in exports from sectors such as fishing, animals (products), meat, forestry, and services. The remarkable rise in fishing exports, primarily driven by the expansive marine resources available, signifies a potential avenue for sustaining higher yields without the immediate constraints posed by land availability.

However, amidst these shifts, there is an evident strain on the agricultural sector due to the escalating cost of water, particularly impacting crops like rice, wheat, and sugarcane, which are substantial consumers of agricultural water. Consequently, this cost escalation makes domestic production of these crops expensive, leading to a surge in their imports. Moreover, the rising reliance on imported processed food exacerbates the strain on the agricultural sector.

Overall, while the trade balance of the country shows signs of improvement, projected to reach over US$1.2 billion by 2040, the adverse impact of population growth on the economy is conspicuous. The combined effect of escalating water prices, structural changes in production, dwindling agricultural outputs, and diminishing real wages due to population growth results in a significant welfare loss exceeding US$2 billion. Addressing this burgeoning population issue becomes imperative to mitigate the projected losses, indicating a pressing need for strategic interventions and policies to navigate these impending economic challenges.

In conclusion, Pakistan stands at a critical juncture, facing multifaceted challenges driven by the impending surge in population and consequential shifts in economic dynamics. The forecasted trajectory presents a concerning outlook, primarily characterized by escalating water prices, declining agricultural outputs, and structural changes in production, all exacerbated by the burgeoning population.

Addressing these challenges demands immediate and strategic interventions. Policymakers need to prioritize water resource management strategies to alleviate the upward trajectory of water prices, especially concerning crops heavily reliant on agricultural water. Investing in sustainable water conservation methods and irrigation systems could mitigate the impact on crop production costs.

Simultaneously, fostering innovation and technology adoption within the agricultural sector can bolster

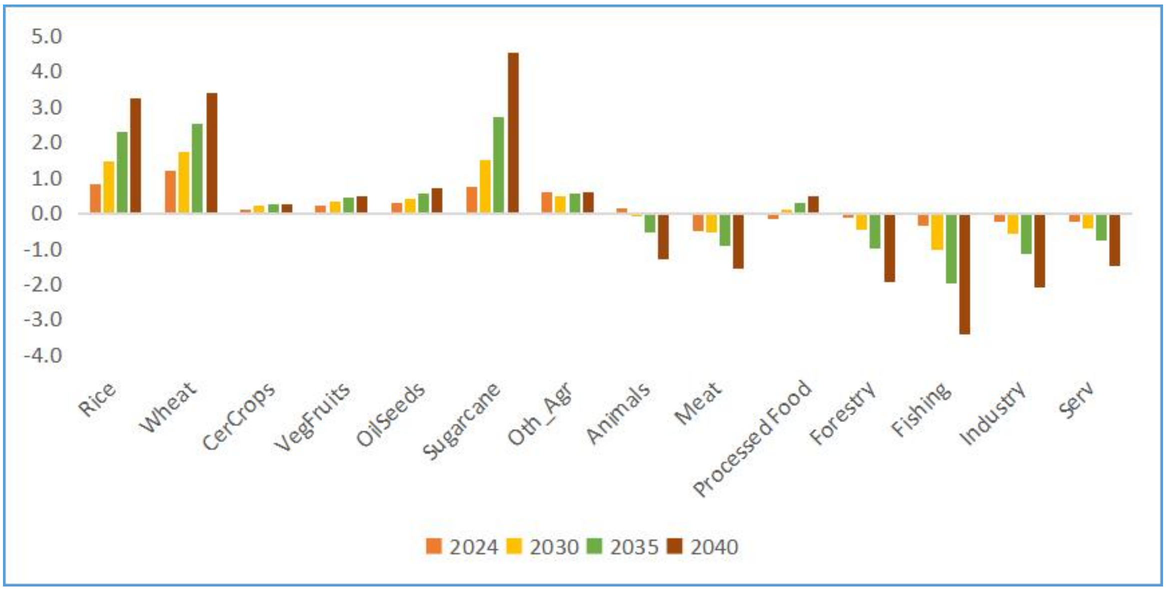

Figure 4. Change in imports (% change from baseline). Source: Authors' calculations.

productivity, ensuring resilience against the anticipated declines in staple crop outputs. This could involve promoting efficient farming practices, introducing drought-resistant crop varieties, and supporting research and development in agriculture.

Additionally, the shifting dietary patterns towards increased meat consumption necessitate a reevaluation of livestock management practices, emphasizing sustainable production methods while aligning with evolving consumer preferences.

Strategically, Pakistan could explore diversification in trade sectors, leveraging the potential of fisheries and other industries witnessing export growth. However, this shift in trade dynamics should align with sustainable resource management to prevent overexploitation of marine resources.

Ultimately, a concerted effort involving governmental initiatives, private sector participation, and community engagement is pivotal to navigate these challenges successfully. By adopting a multifaceted approach that integrates sustainable resource management, technological advancements, and socio-economic strategies, Pakistan can mitigate the adverse effects of population growth, ensuring economic resilience and sustainable development.

8. Recommendations

Based on the discussion of the simulation results, here are some key recommendations:

8.1. Water Resource Management

Implement comprehensive water pricing reforms to reflect the true scarcity value of water and encourage efficient use.

Invest in modern irrigation technologies (e.g., drip irrigation, precision agriculture) to improve water use efficiency in agriculture.

Develop and enforce strict regulations on groundwater extraction to prevent overexploitation.

Invest in water storage infrastructure to better manage seasonal water availability.

8.2. Agricultural Sector Transformation

Promote crop diversification towards less water-intensive, high-value crops.

Provide incentives and support for farmers to adopt water-efficient farming practices.

Invest in research and development of drought-resistant crop varieties.

Develop policies to support sustainable intensification of livestock production to meet growing meat demand while managing environmental impacts.

Figure 5. Change in welfare level and trade balance (US$ million changes from baseline). Source: Authors' calculations.

8.3. Industrial and Service Sector Development

Encourage investment in water-efficient industrial processes and technologies.

Promote the development of service sectors that are less water-intensive to support economic diversification.

Implement policies to facilitate the transition of labor from agriculture to industry and services, including skill development programs.

8.4. Trade and Food Security

Develop a strategic approach to food imports, focusing on water-intensive crops while promoting exports in sectors where Pakistan has a comparative advantage.

Strengthen domestic food production capacity in key areas to ensure food security.

Explore and invest in the potential of the fishing industry as a significant export sector.

8.5. Population and Human Capital

Implement comprehensive population planning policies to manage population growth.

Invest in education and skill development to improve labor productivity and facilitate economic structural transformation.

Develop urban planning strategies to manage rural-urban migration and ensure sustainable urban growth.

8.6. Climate Change Adaptation

Integrate climate change projections into long-term water resource planning.

Invest in climate-resilient agriculture and infrastructure.

8.7. Regional Development

Develop region-specific water management and agricultural development strategies to address varying impacts on rainfed and irrigated areas.

Promote balanced regional development to manage potential disparities arising from water availability.

8.8. Research and Technology

Increase investment in water-related research and technology development.

Promote the use of data analytics and remote sensing for better water resource management and agricultural planning.

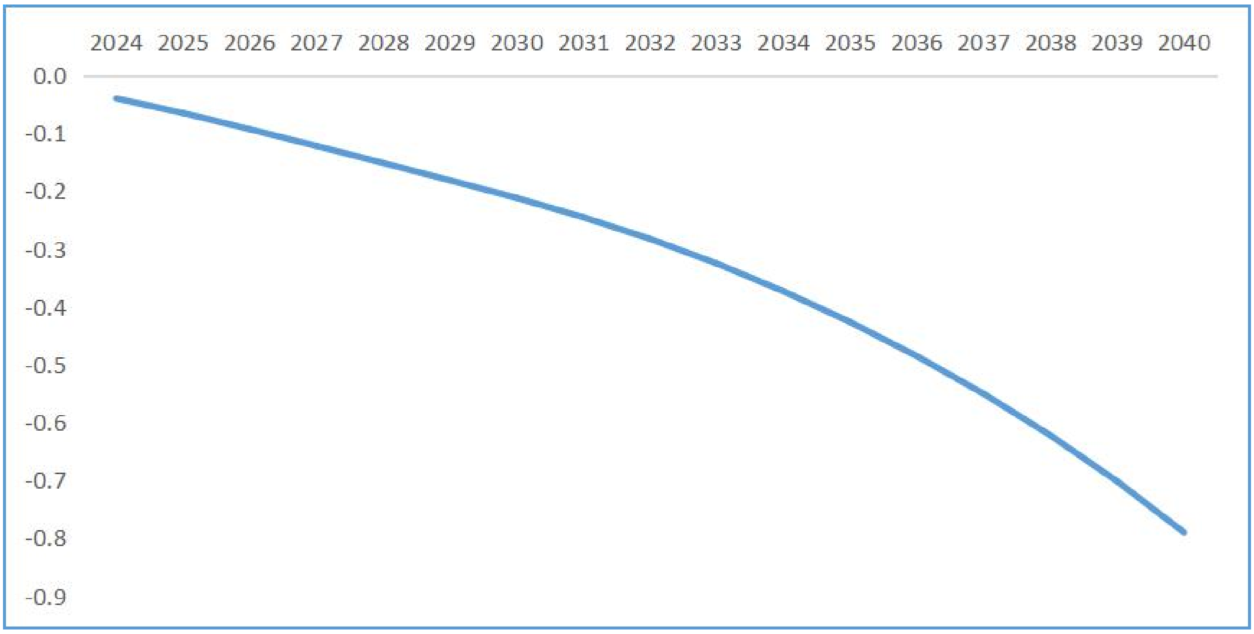

Figure 6. GDP growth rate (% change from baseline). Source: Authors' calculations.

8.9. Institutional Reforms

Strengthen water governance institutions to improve coordination and enforcement of water-related policies.

Develop public-private partnerships for water infrastructure development and management.

8.10. International Cooperation

Engage in regional water-sharing agreements and cooperation on transboundary water resources.

Seek international support and knowledge transfer for water management and agricultural modernization.

These recommendations aim to address the challenges identified in the simulation results, focusing on improving water use efficiency, facilitating economic structural transformation, ensuring food security, and managing the impacts of population growth and climate change. Implementation would require a coordinated effort across various government departments, as well as collaboration with the private sector, international organizations, and local communities.

Author Contributions

Zeshan has proposed and estimated the theocratical and econometric models. Shakeel has developed the introduction, literature review and conclusion sections. Ferraira revised the entire draft for improvement.

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We declare that the views expressed in the present work are those of the authors and not of their respective institutions.

Data Availability Statement

The datasets generated during and/or analyzed during the current study are available in the [GTAP] repository, [https://www.gtap.agecon.purdue.edu/databases/v11/].

Conflict of Interest

There is no conflict of interests by any author of the study.

Appendix A

List 1. List of model variables and parameters.

$qfe_{i,j,r}$	demand for endowment i for use in industry j in region r
$qlw_{j,r}$	composite "irrigable land+water" in industry j of region r
$pfe_{i,j,r}$	firms' price for endowment commodity i in industry j of region r
$plw_{j,r}$	firms' price of "irrigable land+water" composite in industry j of region r
$afe_{i,j,r}$	primary factor i augmenting technical change by industry j of region r
$ELLW_{j,r}$	elasticity of substitution between irrigable land and water in j
$SLW_{i,j,r}$	share of i in the composite good "irrigable land+water"

List 2. Dynamics in the model.

The dynamic CGE water model (Gdyn-W) introduces dynamics in several key ways:

1. Recursive Dynamic Structure:

The model employs a recursive dynamic setting, where economic decisions are made sequentially over time. This approach allows the model to capture how the economy evolves and how decisions at different points in time influence each other.

2. Capital Mobility:

A distinguishing feature of the dynamic GTAP model is its disequilibrium approach to capital mobility. The model:

- Maintains short-term and medium-term differences in rates of return
- Allows for imperfect capital movement between regions in the short to medium term
- Permits perfect capital mobility in the long term

This approach provides a more realistic representation of how capital flows adjust over time in response to economic changes.

3. Time Horizon:

The model is set up to analyze economic impacts across time, and projections are made up to 2040. This allows for the examination of long-term trends and impacts.

4. Evolving State of the Economy:

The model takes into account the changing state of the economy over time. This includes factors such as:

- Population growth
- Changes in factor prices (e.g., water prices)
- Structural changes in production patterns
- Shifts in trade dynamics

5. Interacting Economic Agents:

The dynamic CGE model captures the intricate interdependencies between different economic agents over time. This includes interactions between:

- Various sectors of the economy
- Agents
- Markets

6. Incorporation of Exogenous Changes:

The model allows for the incorporation of exogenous changes over time, such as:

- Population growth (explicitly mentioned in the document)
- Technological advancements (implied, though not explicitly discussed in the given text)
- Policy changes (implied, though not explicitly discussed in the given text)

By introducing these dynamic elements, the GTAP dynamic model provides a more sophisticated tool for analyzing complex economic phenomena over time. It allows researchers and policymakers to examine how various factors interact and evolve, providing insights into long-term economic trajectories and the potential impacts of policy decisions or demographic changes.

However, it is worth noting that the document does not provide a complete technical explanation of all dynamic elements in the model. A more comprehensive understanding would require additional information on aspects, such as the specific equations governing intertemporal decisions, the treatment of expectations, and any other dynamic features not mentioned in this particular document.

While the current study provides valuable insights into the impacts of population growth and water scarcity in Pakistan, a thorough examination of the robustness to our aggregation methods significantly strengthens its conclusions. By systematically testing different aggregation schemes and validating key parameters, the study provides a more reliable basis for long-term policy planning in Pakistan's water and agricultural sectors.

Table A1. Aggregation scheme.

Number	Code	Description (Detailed Sector Breakdown)	Gdyn-W
1	pdr	Paddy rice	Rice
2	wht	Wheat	Wheat
3	gro	Cereal grains nec	CerCrops
4	v_f	Vegetables, fruit, nuts	VegFruits
5	osd	Oil seeds	OilSeeds
6	c_b	Sugar cane, sugar beet	Sugarcane
7	pfb	Plant-based fibers	Oth_Agr
8	ocr	Crops nec	Oth_Agr
9	ctl	Bovine cattle, sheep and goats, horses	Animals
10	oap	Animal products nec	Meat
11	rmk	Raw milk	Animals
12	wol	Wool, silk-worm cocoons	Oth_Agr
13	frs	Forestry	Forestry
14	fsh	Fishing	Fishing
15	coa	Coal	Industry
16	oil	Oil	Industry
17	gas	Gas	Industry
18	oxt	Other Extraction (formerly omn Minerals nec)	Industry
19	cmt	Bovine meat products	Processed Food
20	omt	Meat products nec	Processed Food
21	vol	Vegetable oils and fats	Processed Food
22	mil	Dairy products	Processed Food
23	pcr	Processed rice	Processed Food
24	sgr	Sugar	Processed Food
25	ofd	Food products nec	Processed Food
26	b_t	Beverages and tobacco products	Processed Food
27	tex	Textiles	Industry
28	wap	Wearing apparel	Industry
29	lea	Leather products	Industry
30	lum	Wood products	Industry
31	ppp	Paper products, publishing	Industry
32	p_c	Petroleum, coal products	Industry
33	chm	Chemical products	Industry
34	bph	Basic pharmaceutical products	Industry
35	rpp	Rubber and plastic products	Industry
36	nmm	Mineral products nec	Industry
37	i_s	Ferrous metals	Industry
38	nfm	Metals nec	Industry
39	fmp	Metal products	Industry
40	ele	Computer, electronic and optical products	Industry
41	eeq	Electrical equipment	Industry
42	ome	Machinery and equipment nec	Industry
43	mvh	Motor vehicles and parts	Industry
44	otn	Transport equipment nec	Industry
45	omf	Manufactures nec	Industry
46	ely	Electricity	Industry
47	gdt	Gas manufacture, distribution	Industry
48	wtr	Water	Industry
49	cns	Construction	Industry
50	trd	Trade	Serv
51	afs	Accommodation, Food and service activities	Serv
52	otp	Transport nec	Serv
53	wtp	Water transport	Serv
54	atp	Air transport	Serv
55	whs	Warehousing and support activities	Serv

Table A1. *Cont.*

Number	Code	Description (Detailed Sector Breakdown)	Gdyn-W
56	cmn	Communication	Serv
57	ofi	Financial services nec	Serv
58	ins	Insurance (formerly isr)	Serv
59	rsa	Real estate activities	Serv
60	obs	Business services nec	Serv
61	ros	Recreational and other services	Serv
62	osg	Public Administration and defense	Serv
63	edu	Education	Serv
64	hht	Human health and social work activities	Serv
65	dwe	Dwellings	Serv

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