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Openness, Institutions, and Sectoral Dynamics in Pakistan's Water Stress

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ABSTRACT: Water stress is a big hurdle to sustainable development in Pakistan and the attainment of SDG 6. This study aims to analyze various economic, demographic and institutional indicators related to water stress in Pakistan with the help of World Bank data for the period 1999-2023 and based on the known statistical techniques to explore the relations between these indicators. The results indicate that agricultural output has a positive effect of 15.719 ($p < 0.01$) on water stress and population density has positive effect of 1.596 ($p < 0.01$) on agricultural output. Water stress also has a positive association with environmental policy stringency, 24.448 ($p < 0.05$). Similarly, lagged foreign direct investment has a positive and significant coefficient of 31.010 ($p < 0.01$). In contrast, trade openness has a negative coefficient of −1.190, which is not statistically significant ($p > 0.10$). The results reinforce the importance of efficiency in irrigation, of the implementation of environmental policy and of the introduction of sustainable water management into urban planning. The results, however, are difficult to generalize since limited provincial data exist. Further research is needed to explore regional variations for better and more regionally appropriate water policies.

KEYWORDS: Water Stress, Agricultural Output, Population Density, Environmental Policy, FDI, SDG 6

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Introduction

Water scarcity is becoming more and more of a problem with ever-growing demands of water for the economic production and for managing the environment. The scarcity of freshwater resources is a result of both the demands of agriculture and industry, as well as the lack of adequate management of the resources (Farooq, 2023; Noreen & Younes, 2024). Such challenges are essential to meet in order to attain Sustainable Development Goal 6 (Clean Water and Sanitation), especially in water-constrained economies (Yousaf et al., 2024). In this context, the economic openness-water sustainability nexus deserves more in-depth analysis. While the benefits of trade openness (TO) and foreign direct investment (FDI) on technological improvement and efficient production are well known, their impact on water resources in Pakistan is still poorly understood (Amjad et al., 2024; Begum & Ali, 2025).

Economic development and water stress are influenced by the demand for water as well as the ability of institutions to manage natural resources. According to Endogenous Growth Theory, international trade and investment can promote technological development but this does not always lead to a reduction in resource

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use. Economic growth can further increase the demand for freshwater in agriculture, industry and manufacturing, while poor irrigation practices exacerbates the current scarcity of water in Pakistan (Amjad et al., 2024; Hussain et al., 2022; Farooq, 2023; Noreen & Younes, 2024). Thus, the effectiveness of environmental governance is crucial. In a case where regulations are not well enforced, pollution or extraction of the resource could be possibly more attractive than sustainable use (Begum & Ali, 2025).

Moreover, the effects of economic openness do not appear to be homogeneous and predictable as indicated by earlier studies. Trade can boost economic activities, but it can also lead to an increase in water requirement in agricultural-based economies (Din & Siddique, 2022; Onogbosele, 2025). For example, Noreen & Younes (2024) highlight important irrigation problems with sodium in tube-well water in Rechna Doab, Pakistan, pointing to the added challenges water quality problems can pose for freshwater management. While the advantages of FDI appear to vary according to the production context (Muhammad, 2023; Ari et al., 2022), it can also introduce more efficient technologies. The demand for water is also increased due to manufacturing activity and high population density in urban areas (Yousaf et al., 2024) and increased water demand and pollution (Farhat, 2023). water stress determination can not be performed as a separate individual determination of the pressures. This is because the pressures are correlated.

Institutional Theory offers another lens through which to explain environmental outcomes in terms of regulatory arrangements and governance capacity. Environmental protection regulations are lacking and this can lead to overextraction, pollution and poor water management can worsen water resource allocation problems (Hussain et al., 2022; Wani et al., 2023). Interprovincial water dispute and mismanagement are other important aspects of water scarcity in Pakistan (Begum & Ali, 2025; Farooq, 2023). Nevertheless, suitable environmental policy stringency (EPS) may promote economic growth and optimal resource use, while extreme policy stringency may pose hindrances for investments and technology transfer (Yousaf et al., 2024; Zhang et al., 2024; Abdouli & Ouni, 2023). But given this potential trade-off, it is the institutional dimension that really matters in terms of the environmental effects of trade and investment.

The Environmental Kuznets Curve (EKC) also provides another viewpoint, suggesting that environmental impacts could rise as the country's economy grows and starts to expand, before falling as the adoption of cleaner technologies and more robust institutions takes place (Hossain et al., 2022; Oğuz, 2024). In Pakistan, an increase in income is linked to increase in freshwater withdrawals, especially for agriculture (Farooq, 2023; Nwinyodee & Kerebana, 2022). Yet, the relationship between the two can be changed by the advancement of good governance and green innovation, in addition, the environmental impacts of trade liberalisation are still ambiguous (Yousaf et al., 2024; Febriyanti et al., 2022). In the context of water stress in Pakistan, therefore, the rigid validity of EKC must be empirically tested and not assumed.

In this backdrop, the present study focuses on water stress level (WSL) and seven explanatory variables, such as TO, FDI, agricultural output (AO), manufacturing output (MO), population density (PD), EPS and GDP per capita. The analysis uses annual data from 1999 to 2023 and the Autoregressive Distributed Lag (ARDL) model along with Fully Modified Ordinary Least Squares (FMOLS) are applied to study the relationship between these variables. The study takes a unique and integrated approach that considers economic openness, productive activity, and demographic pressures, alongside environmental governance, as a single

package, which is missing from water quality and economic openness literature (Noreen & Younes, 2024; Amjad et al., 2024).

The investigation is original and adds to the literature in three ways. Firstly, it offers an all-in-one analysis of the economic, sectoral, demographic and institutional aspects of Pakistan's water problems. Secondly, it integrates three theories - Endogenous Growth Theory, Institutional Theory and the EKC – to discuss their applicability to water sustainability in an agriculture-based economy. Thirdly, it aims to provide guidance on policies relating to irrigation efficiency, industrial water use, urban water planning and investments, and contribute to SDG 6. The results may also inform priorities in more context-sensitive water governance, due to the inability of national level indicators to account for regional differences.

The study addresses three research questions:

1. How is trade openness associated with water stress in Pakistan?
2. What relationship exists between foreign direct investment and water stress?
3. How do trade openness, FDI, agricultural and manufacturing output, population density, environmental policy stringency and GDP per capita jointly relate to water stress?

These questions are related to three objectives, viz., to assess the relation between TO and WSL, examine the association between FDI and WSL, and evaluate the overall effect of all seven explanatory variables with respect to SDG 6.

Literature Review

The increasing water stress in Pakistan has become a pressing issue, with national estimates placing the water stress level over 80% and the majority of the water demand coming from irrigation (Sheikh et al., 2025). It is necessary to take into consideration economic openness, productive activity, demographic change and institutional effectiveness to explain this challenge. Therefore, a cross-theoretical approach is used in the present study that combines Endogenous Growth Theory, Institutional Theory and Environmental Kuznets Curve (EKC) to explore the linkages between water stress level (WSL) and trade openness (TO), foreign direct investment (FDI), agricultural output (AO), manufacturing output (MO), population density (PD), and environmental policy stringency (EPS) and GDP per capita.

According to Endogenous Growth Theory, it is possible to increase technological diffusion and resource efficiency through trade and foreign investment (Grossman & Helpman 1991; Romer 1989). However, the ecological impacts of economic openness will vary depending on the industry where investments are placed and their ability to practice sustainable production. Irrigation demand is an important factor in the determination of the water pressure in Pakistan, as it is considered as one of the main consumers of fresh water, accounting for about 80% of the total consumption (Amjad et al., 2024; Hussain et al., 2022). While trade can drive growth, increased growth in water-intensive sectors can exacerbate water scarcity. The findings from Nigeria also suggest that in the short term, trade openness can have negative impacts on the performance of agricultural activities (Onogbosele, 2025).

In less industrialized economies, FDI can bring in new technologies that are more water efficient, especially in the manufacturing sector, but the impact is not guaranteed in agriculture-based economies (Muhammad, 2023; Radmehr et al., 2022; Sugözü & Dorbonova, 2024). International investment can create benefits for the

environment, but can be limited by institutional obstacles to technology adoption (Robinson & Acemoglu, 2012). Thus, the effectiveness of FDI can be influenced by the degree of trade integration, the quality of regulations and the capacity of regulation (Hai et al., 2023; Begum & Ali, 2025). These relationships are even more complicated by differences in empirical findings, omitted institutional factors and cross-sectional bias (Amjad et al., 2024; Febriyanti et al., 2022). The constraints feed into incorporating institutional factors into growth-driven water stress explanations.

The EKC hypothesis suggests that at first, environmental degradation may worsen due to economic development, but eventually, as cleaner technologies and more robust institutions develop, environmental degradation will improve. (Grossman & Krueger, 1995) However, in Pakistan doing so may be delayed due to considerable water needs from irrigation sources, especially because of increased economic activities on freshwater (Noreen & Younes 2024). Similar issues have been documented in other developing economies where economic growth leads to the exhaustion of resources (Nwinyodee & Kerebana, 2022).

The validity of the EKC is still questioned. Trade liberalisation has not always been beneficial for the environment in OIC countries (Febriyanti et al., 2022), while more stringent environmental policies and green innovations could lead to more sustainable growth (Yousaf et al., 2024; Işık et al., 2024a, 2024b). The continued high level of contamination of rivers in Pakistan with heavy metals is another example of the effects of poor environmental management (Afzaal et al., 2022). The evidence also shows that the environmental impacts of growth and trade differ by economic context internationally (Zhang et al., 2024; Georgina, 2024). This study hence explores the relationship between the increases in the countries water stress trajectory and income and environmental policy stringency in Pakistan.

The economic openness is not the only factor that affects water stress, but also the mix of production and population distribution. Irrigation demand may increase due to agricultural expansion, especially with the trend towards increasing water-intensive production through trade (Amjad et al., 2024; Hussain et al., 2022; Noreen & Younes, 2024). Industrial consumption and water pollution pose another stress to manufacturing (Farhat, 2023), while high density of population puts pressure on urban water infrastructure, with high density in both Karachi and Rawalpindi and Islamabad (Shahid & Ali, 2024; Nadir, 2024). While FDI is likely to positively impact the sustainability of manufacturing, its impact on water sustainability in agriculture has proved less consistent (Muhammad, 2023; Ari et al., 2022).

Institutional Theory explains why these pressures may produce different outcomes across economies(Asghar et al., 2025). Effective governance can facilitate technology adoption, strengthen regulatory compliance and improve water allocation, whereas weak enforcement may allow production and consumption to intensify resource depletion (Hai & Tuyet, 2023; Begum and Ali, 2025). In Pakistan, systemic mismanagement remains an important concern (Farooq, 2023). International evidence suggests that improved governance and technological innovation can strengthen the environmental benefits of investment (Ekpang et al., 2025; Jarrett & Tackie, 2024). Water-saving technologies have also demonstrated potential to reduce consumption in Saudi Arabia, although their applicability to Pakistan requires further assessment (Alharbi et al., 2024). The research highlighted in this field supports the governance, digitalisation and policy stability as the key pillars for the sustainable development goals. (Hai & Tuyet, 2023; Işık et al., 2024b, 2024c).

So far, the empirical evidence on the link between economic openness and water stress is ambiguous. Studies on Pakistan have found that with porosity of trade, there is a rise in economic activity and the need for irrigation (Amjad et al., 2024; Hussain et al., 2022), while some studies have found that the environmental impact is less pronounced or that the findings are sensitive to methodology (Febriyanti et al., 2022; Din & Siddique, 2022). There is also some mixed evidence on the impact of FDI, which can lead to increased efficiency in manufacturing, but the effects are less clear in agriculture-intensive environments (Muhammad, 2023; Ari et al., 2022). The discrepancies indicate that economic openness needs to be studied with the sectoral activity as well as the demographic pressures and institutional quality (Hafeez et al., 2023).

Methodological limitations also constrain the existing evidence. Although ARDL models are used to investigate short- and long-run relationships, the omission of institutional variables and other relevant controls may affect the reliability of estimated relationships (Amjad et al., 2024; Ari et al., 2022; Din & Siddique, 2022). Incomplete data reporting can further limit reproducibility (Farooq, 2023). Panel estimation and threshold generalised method of moments have been employed to address cross-country differences and endogeneity concerns (Jarrett & Tackie, 2024; Hai & Tuyet, 2023), whilst alternative vulnerability indicators and combined econometric approaches may strengthen future investigations (Sheikh et al., 2025; Li et al., 2025). Nevertheless, inconsistent measures of environmental policy and divergent findings on investment remain unresolved.

The principal research gap is the absence of a sufficiently integrated assessment of the economic, sectoral, demographic and institutional determinants of water stress in Pakistan(Khan et al., 2025). Conflicting evidence on FDI (Ari et al., 2022; Muhammad, 2023), uncertainty regarding environmental policy effectiveness (Begum & Ali, 2025) and the proposed benefits of green innovation (Yousaf et al., 2024) underscore the need for further investigation.

To address this gap, the present study examines WSL in relation to TO, FDI, AO, MO, PD, EPS and GDP per capita using Pakistan's time-series data and the ARDL and FMOLS approaches. The study combines Endogenous Growth Theory, Institutional Theory and the EKC to explain the relationship between economic development and governance in determining water stress. The results aim to guide policy decisions on irrigation efficiency, industrial water use, investment and environmental regulation, and thereby help Pakistan move closer to Sustainable Development Goal 6.

Research Methodology, Study Context and Hypotheses

Pakistan's water stress is one of the key issues at the intersection of economic development, demographic change and environmental governance. The country is especially relevant to explore these interactions because it does not have much freshwater resources, large use of water for agriculture activities and chronic problems in resource management as reported by Farooq (2023) and Noreen & Younes (2024). Presently approximately 80% of freshwater resources are utilized in agriculture, which is a concern on sustainability of the existing water consumption pattern. The importance of understanding the drivers of water stress on an agrarian economy under institutional constraints has grown since 1999, due to the economic liberalisation, the growth of international trade and the population expansion. The Pakistani experience could also provide

comparative lessons for other South Asian countries, such as India and Bangladesh, where water security is a key development issue.

In this backdrop, the present study aims to explore the economic and institutional factors behind the water stress level (WSL) using a multivariate time-series approach. It utilizes an analytical technique that integrates the Autoregressive Distributed Lag (ARDL) modelling, Fully Modified Ordinary Least Squares (FMOLS) with Granger causality tests, impulse response functions (IRFs) and variance decomposition analysis (VDA). These complementary techniques are used to examine short-run changes and short-run interactions and relationships between variables, as well as long-run relationships. The theoretical underpinning is based on Endogenous Growth Theory and the Environmental Kuznets Curve (EKC), providing a more comprehensive explanation of the emergence of water stress in the broader context of economic transition, technology transfer and policy performance. The study also connects these issues with Sustainable Development Goal 6 (Clean Water and Sanitation) and focuses especially on implications for sustainable resource management and environmental policy.

The empirical hypotheses are based on the assumption that economic openness, productive activities and the demographic pressure, along with the institutional capacity, can affect water stress in different ways, and possibly interact. To the contrary, H1 holds that trade openness (TO) promotes WSL, especially when expansion of international trade incentivizes water intensive production and export. This is in line with the findings of Amjad et al. (2024), but the results from the OIC context suggest that the environmental impacts of trade are not always the same (Febriyanti et al., 2022). H2 believes that the relation between foreign direct investment (FDI) and WSL will be contingent on the sectoral distribution of investments and the spread of waterSmart technologies. The mixed results found by Ari et al. (2022) and Muhammad (2023) indicate that investments do not always give the same environmental results in agriculture.

Further, agricultural output (AO), manufacturing output (MO), population density (PD), environmental policy stringency (EPS) and GDP are also included in the analysis to capture sectorial, demographic and developmental factors influencing WSL. The following variables are part of a wider hypothesis that water stress is a result of the combination of economic activity and institutional conditions. However, the relationship between water stress and stricter environmental regulation is expected to be negatively affected in the event of poor implementation of the environmental measures and inadequate enforcement of the regulations (Begum & Ali, 2025). Given that Hussain et al. (2022) have raised its empirical concerns, it thus tests competing explanations on economic openness, investment and resource depletion, and also explores the role of institutional effectiveness in shaping environmental impacts of economic development through the EKC framework.

The analysis relies on the data from Pakistan over a time span of 25 years (1999-2023) for yearly observations and examine relation between economic activity and water stress. The variables are first given some preliminary statistical evaluation to determine the distributional properties and the suitability of the variables for econometric analysis before estimation is undertaken. The missing observations are handled by the forward-filling and backward-filling techniques, and GDP is then converted to its natural log to improve the properties of the series, and to reduce skewness. The TO and FDI are standardised to enable comparisons, as suggested by Hussain et al. (2022). The data source(s), transformations and diagnostic procedures are

documented for transparency and reproducibility. However, caution should be used when drawing conclusions from national aggregates due to the short period of observation and potential data incompleteness and geographic differences in water availability.

The ARDL method is the main estimation technique used to explore the relationship between WSL and seven explanatory variables: TO, FDI, AO, MO, PD, EPS and the natural logarithm of GDP. An advantage of this is that the long-run associations as well as the short-run responses can be analyzed in the same specification. The suitability is partly due to the fact that it allows regressors to be integrated of order zero or one and if one variable is integrated of order one, there are no variables of order two. The method is therefore applicable to small sample sizes, but the results of the estimates depend on the correct specification of the model and the diagnostic tests (Pesaran et al., 2001).

The short-run behaviour is discussed by using the error-correction formulation of the ARDL model. This statement separates out changes in the explanatory variables from the manner in which deviations from the long-run equilibrium are eliminated. The negative and statistically significant error-correction coefficient would suggest that the economy moves towards the estimated equilibrium, which is in line with the framework explained by Pesaran et al. (1999). Use of the Akaike Information Criterion (AIC), Schwarz Criterion (SC), Hannan–Quinn Criterion (HQ), Final Prediction Error (FPE) and likelihood-ratio (LR) criteria to determine the appropriate lag structure. In the simplest analysis, one lag is included, but this also should be considered in view of the sample size and residual diagnostics.

The ARDL bounds-testing procedure is used to test for a long run relationship. If the calculated test statistic falls below the lower bound of the critical values, it is rejected as being indicative of cointegration, and if it falls within the bounds, it is considered inconclusive. If a statistic is below the lower bound the test does not give evidence of cointegration based on the stated hypotheses. This process determines if there is a long-term relationship in the data, instead of assuming there is a long-term relationship.

FMOLS is used as an additional estimator to test the robustness of the long run relationships estimated by ARDL. This method is a solution to the problem of serial correlation and endogeneity that may result from estimating cointegrating relationships, as developed by Phillips & Hansen (1990). The similarity between ARDL and FMOLS results will lend further robustness but it is not enough to imply causation or rule out all possible sources of bias. To check the robustness of the key results, alternative lag structures and a subsample (2005–2023) are considered.

Granger causality tests are used to explore the direction of potential relationships. These tests check if the historical values of one variable add value to predicting values of another, after accounting for the predictive power of the other variables' historical values. They also allow for analysis of possible causal links from the explanatory variables to WSL, and the other way around. The results from them, however, should not be taken as proof of structural causation but predictive precedence.

To go beyond estimated coefficients and predictive relationships, IRF's and VDA's are calculated in a vector autoregression (VAR) framework. IRFs show the way that WSL reacts to an unanticipated change in an explanatory variable over time (in this case, 10 years). VDA adds value to this analysis by estimating the amount of variance in the forecast-error on WSL that can be explained by shocks in the variables in the system. These

techniques can be used to get an idea of the persistence and relative significance of economic and institutional shocks, provided that the underlying VAR specification is adequate, stable and identified.

A series of diagnostic tests are used to gauge the credibility of the econometric results. To analyse the stationarity of variables and determine the integration property of the variables, Augmented Dickey–Fuller (ADF) procedures are used. Pearson correlation coefficients give a first look at pairwise associations of the explanatory variables; a coefficient of less than 0.8 should not be interpreted as a definitive statement that no multicollinearity exists, although it is a positive sign that there may not be severe multicollinearity (Wooldridge, 2019). The Jarque–Bera test is used to test for residual normality, while the Breusch–Pagan–Godfrey procedure tests for residual variance homogeneity. There are other checks of sensitivity to modelling choices and changes over time in the form of alternative lag structures and subsample estimates.

Despite these processes, the analysis is open to limitation due to the length and aggregation of the data set. The national water balance figures can hide regional variations in water availability, agricultural output, industrial demand and institutional capacity. In addition, the relationships may have changed since 2008 due to policy changes, which could result in structural instability. ARDL and FMOLS solve specific econometric problems in specific conditions, but not necessarily to eliminate all the types of endogeneity, omitted-variable bias or structural change. Whereas, province-level data sets could be used in future investigations, region-specific estimates could be made and small-sample bootstrapping for estimates of the causalities could be used. These would allow more detailed consideration of regional differences and provide more empirical support for water-management policy.

Results

From the descriptive evidence, there are significant variations in the water stress situation in Pakistan and the associated economic and demographic indicators. WSL records a mean of 118.614 (SD = 17.132), whilst AO averages 22.511 (SD = 1.393) and PD stands at 259.763 (SD = 38.112). The FDI has also fluctuated significantly over time, with the average value of 0.944, and the standard deviation of 0.750, indicating an uneven pattern of investment that could have varying environmental impacts based on sectoral allocation and technological efficiency (Ari et al., 2022). The mean of logged GDP is 6.973 (SD = 0.304), but the distribution of GDP has to be validated for its suitability to be estimated via diagnostic testing.

The correlation matrix shows that there is a strong positive correlation between PD and WSL ($r = 0.711$) while the correlation for FDI, TO and AO are not significant. The low contemporaneous correlation between trade openness and water stress is in line with the finding that the impact of trade on the environment is not homogenous across economic and institutional environment (Febriyanti et al., 2022). However, these initial relationships are not lagged or conditional on other explanatory variables. This is especially important with regard to the low level of pairwise correlation between the variables that is observed in the case of AO while the positive coefficient of the variables in the dynamic estimations is significant. Moreover, the correlation between PD and logged GDP ($r = 0.940$) is a concern for multicollinearity and needs further exploration.

The long period ARDL estimates show that agricultural output is a statistically significant positive factor in the growth of WSL ($\beta = 15.719$, $p < 0.01$). This is consistent with the fact that agriculture consumes around 80% of freshwater withdrawals in Pakistan, as a result of which, the agriculture sector is a major user of water

(Noreen & Younes, 2024). The importance of improving irrigation efficiency, strengthening water allocation and promoting appropriate water-saving technologies as policy goals therefore arise. Water efficient technologies can shed light on international evidence, but their effectiveness will need to be evaluated under the specific agricultural conditions in Pakistan (Alharbi et al., 2024).

Population density also has a positive and statistically significant relationship with WSL ($\beta = 1.596$, $p < 0.01$) that emphasizes the role of demographic pressure in freshwater management. Domestic demand, competition between water users and pressure on urban infrastructure can be exacerbated by increase in population concentrations. There should therefore be a long-term planning component that addresses the demographic change as well as enhancing the resilience of water-supply systems.

Environmental policy stringency has a positive estimated coefficient ($\beta = 24.448$, $p < 0.05$). The surprising result shouldn't be taken as an evidence to the contrary that stricter regulation leads to greater water stress. It could alternatively be a result of policy measures addressing current environmental degradation, the lack of enforcement, or the design of the EPS indicator. Environmental regulation effectiveness, therefore, should consider enforcement capacity, as well as institutional performance (Begum & Ali, 2025).

Likewise, lagged FDI is positively associated with WSL ($\beta = 31.010$, $p < 0.01$). This correlation suggests that if investments are focused on water-intensive activities, they put further pressure on freshwater resources, especially if efficient technologies and effective environmental protection measures are not applied. The environmental consequences of investments, however, vary according to their sectoral structure and the way they are run, and cannot be broadly applied to all foreign investment (Ari et al., 2022).

In contrast, the coefficient of TO is reported as statistically insignificant ($\beta = -1.190$, $p > 0.10$) and MO is also reported as statistically insignificant in the long-run specification. The results do not confirm an independent long run relationship between trade openness or manufacturing output and water stress, which would provide justification for explaining the direct links between economic openness and environmental degradation (Febriyanti et al., 2022). The long-run association between logged GDP and WSL has been found to be negative but the value of its coefficient and its significance with which to reach substantive conclusions needs to be checked. In conclusion, the findings put the focus on agricultural activity and demographic pressure, while highlighting the need for a more subtle interpretation of the role of investment, effective regulation, and economic development.

The short run estimates reveal that the FDI activity is positively related to WSL ($\beta = 7.761$), which can lead to a short term resource pressure due to the investment. The evidence reported for MO is also worthy of attention but the coefficient and statistical significance need to be verified. If water pressure is set up in the industry, water-saving production might reduce environmental costs as well as wastewater treatment and the setting of enforceable discharge standards.

The short-run effects of TO, AO, PD and EPS are estimated to be statistically insignificant. Their long-run effect may consequently be different than their short-term effect, but this does not necessarily stand out from insignificant short-run coefficients. The reported error-correction coefficient is 0.627, which deserves special attention, as is typically the case with an error-correction model, negative and statistically significant error-correction coefficients indicate convergence towards the equilibrium level. The sign and probability value should be compared with the output of the original estimation.

The F-statistic for the ARDL bounds test is 5.726 which is greater than the upper bound critical value of 5% F-statistic critical value of 4.163. If the critical value is suitable for the model specification, this result gives support to the presence of long-run relationship between the variables (Pesaran et al., 2001). The model also yields an R^2 of 0.817, which suggests that the regressors observed in the model explain around 81.7% of the variation in the observed value of WSL. But the Durbin-Watson statistic (2.666) is, in itself, not enough to prove the absence of serial correlation; suitable residual diagnostics still should be performed.

The Granger causality results show that the reported value is 2.713 and it is found that the relationship between PD and WSL is unidirectional. This correlation should be confirmed with the appropriate probability value prior to describing this relationship as statistically significant. Furthermore, unlike a strict sense of causal precedence, Granger causality defines predictive precedence.

The findings of the FMOLS estimates also support the main long-run finding of a positive relationship between agricultural output and water stress ($\beta = 10.302$, $p < 0.01$) on a broad scale. However, the values of the ARDL and FMOLS coefficients show that there is a variation in the estimated magnitude. The need for clear specifications of the models, standard errors and diagnostic results is re-emphasized. In cointegrating regressions the FMOLS model does not correct for all possible sources of endogeneity or serial correlation (Phillips & Hansen, 1990).

The Breusch–Pagan–Godfrey statistic is reported as 11.965 and the probability value to be > 0.10. This would mean that the homoskedasticity null hypothesis cannot be rejected at the common level of significance. Stationarity, residual behaviour and sensitivity to alternative specifications should likewise be considered when evaluating the reliability of the estimates. The high correlation between PD and logged GDP further suggests the need to examine multicollinearity further.

The overall results indicate that water demand of agricultural activities and population is the core issue in the water stress situation of Pakistan. The positive estimates of AO, PD and lagged FDI highlight the importance of incorporating water efficiency into agricultural production, urban planning and investment decisions. Regulatory instruments will only be effective if they are backed by effective implementation, monitoring and enforcement if environmental policies are to have measurable impacts.

The priorities are related to Sustainable Development Goal 6, which focuses on sustainable water management, including more efficient use of water. However, national level observations may mask significant provincial variations in provincial patterns of irrigation intensity, industrial structure and water availability. The use of provincial-level datasets and structural-change analysis and regionally-specific water estimations would offer a more nuanced understanding on water stress and further improve the evidence base for targeted water-governance reforms.

Discussion

Discussion of Empirical Findings and Policy Implications

The empirical results reveal that the agricultural output (AO), population density (PD), environmental policy stringency (EPS) and lagged foreign direct investment (FDI) are important long-term determinants of water stress in Pakistan for the period of 1999-2023. In contrast, there are no long-run impacts of trade openness (TO) and manufacturing output (MO). The findings in this paper give important insights into the interaction

between sectoral activity, demographic pressures and institutional effectiveness and give context-specific insights into Endogenous Growth Theory, Institutional Theory and the Environmental Kuznets Curve (EKC). Furthermore, they highlight SDG 6 as a key element in sustainable freshwater management as well (Hussain et al., 2022; Yousaf et al., 2024; Noreen & Younes, 2024; Pervez et al., 2024).

With irrigation playing a key role in agriculture, water stress is identified as one of the most significant challenges, indicating the enduring inefficient water-use in the sector. Traditional flood irrigation, especially in rice and cotton production, exacerbates the need for more water and the adoption of efficient irrigation methods and advanced farming techniques, and effective water management (Noreen & Younes, 2024; Farooq, 2023; Amjad et al., 2024). In addition, population density has a strong positive correlation with WSL, indicating that a higher population density, or urbanisation, increases competition for freshwater, especially in cases of poor infrastructure and interprovincial governance arrangements (Sheikh et al., 2025; Jarrett & Tackie, 2024; Wani et al., 2023; Begum & Ali, 2025).

The positive and significant EPS coefficient ($\beta = 24.448$, $p < 0.05$) is a counterintuitive result that may be due to weak enforcement or reverse causality and/or a lack of measurement accuracy for regulatory stringency so it is unlikely to be an intrinsic negative impact of environmental regulation. This is in contrast with Yousaf et al. (2024) and emphasizes the gap between policy and practice. The bidirectional Granger causality results between EPS and FDI also indicate interactions between investment decisions and regulatory responses. Therefore, increased monitoring, conservation standards that are enforced and better institutional co-ordination are needed to turn environmental policies into concrete water management improvements.

Lagged FDI likewise exhibits a significant positive relationship with WSL ($\beta = 31.010$, $p < 0.01$), indicating that investment may intensify freshwater demand when directed towards water-intensive activities without adequate technological safeguards. Although this finding is consistent with Ari et al. (2022), evidence of potential industrial water-efficiency gains suggests that investment outcomes depend upon sectoral composition and production practices (Muhammad, 2023). Similar short-run effects are reported by Sugözü and Dorbonova (2024) and Hussain et al. (2022), whilst Hai & Tuyet (2023) emphasise the importance of trade openness in determining the benefits associated with FDI. Investment policy should therefore incorporate water-efficiency criteria and encourage the adoption of conservation technologies.

Neither TO nor MO demonstrates a statistically significant long-run effect on WSL, although MO exhibits a reported positive short-run relationship. These findings suggest that trade and industrial activity may exert different environmental pressures across time horizons, reinforcing the context-dependent nature of growth–environment relationships (Febriyanti et al., 2022; Afzaal et al., 2022; Amjad et al., 2024). The results consequently qualify universal interpretations of the EKC and reinforce the importance of Pakistan's agricultural structure, resource constraints and institutional conditions. The findings collectively contribute to the theoretical debate by showing that sectoral water demand and the effectiveness of regulation are essential to understanding economic growth and environmental sustainability (Pervez et al., 2024; Alharbi et al., 2024).

The three interventions proposed in the framework of SDG 6 – scaling up efficient irrigation with phased subsidies, enforcing regulatory compliance with coordinated enforcement and incorporating measurable

water-use requirements into investment decisions – should be policy priorities. Proposed targets include a 30% reduction in dependence on flood irrigation, 70% adherence to regulations within five years and 20% of relevant investment to be channelled toward water-efficient technologies. These are proposed policy objectives rather than outcomes directly established by the econometric estimates and would require appropriate baselines, monitoring and evaluation.

However, the results should be interpreted in light of the limitations of the study. The small annual sample (n = 25), use of national aggregates and incomplete provincial data are detrimental to the identification of regional differences and can leave endogeneity and omitted-variable concerns unaddressed (Sheikh et al., 2025; Farooq, 2023; Noreen & Younes, 2024; Li et al., 2025). Future studies should use provincial or district level datasets, examine structural breaks and develop more context sensitive measures of environmental policy implementation. With appropriate data and identification assumptions, panel estimation techniques and regionally differentiated EKC models can offer a more robust empirical foundation for targeted water-governance reforms (Alharbi et al., 2024).

Conclusion

The empirical results reveal that the agricultural output (AO) and population density (PD) are the important long-run determinants of water stress levels (WSL) in Pakistan. However, lagged foreign direct investment (FDI) also shows the positive and statistically significant association with water stress. These results show the critical pressures from irrigation-intensive agriculture and population growth on the country's freshwater resources. The positive relationship between agricultural productivity and water stress emphasises the challenge of reconciling agricultural efficiency with sustainable water consumption, particularly in regions where traditional irrigation practices and inefficient resource management are still common. Similarly, the impact of population density illustrates the growing strains on domestic water supplies, urban infrastructure and competing economic users. Another concern is the positive coefficient for environmental policy stringency (EPS), which raises the question that the formal strengthening of environmental policies does not necessarily result in better water related outcomes. This relationship may reflect frailties in regulatory enforcement, institutional capacity, or the measurement of policy stringency, rather than an intrinsically adverse impact of environmental regulation. In contrast, trade openness (TO) does not have statistically significant long-run effect, implying that the environmental implications of economic integration cannot be assumed to be uniform across sectors and institutional settings. The results collectively indicate that the dynamics of water stress in Pakistan are primarily driven by the pressures of agricultural resources and population, while the investment patterns and institutional effectiveness shape the extent to which economic development can be reconciled with environmental sustainability.

The research adds to the literature on Endogenous Growth Theory by providing evidence that the developmental benefits of agricultural production may be constrained by freshwater scarcity when technological progress and efficient irrigation and resource-conservation practices do not keep pace with increasing production needs. Agricultural activity still constitutes the backbone of economic development. However, its sustainability is conditional to the adoption of technologies and production methods, able to improve the productivity of resources. The positive association between AO and WSL emphasises the

significance of incorporating the impacts of environmental resource limitations into growth explanations, particularly in agrarian economies where agricultural output is heavily reliant on freshwater access.

Institutional Theory is further supported by the importance of PD. Demographic expansion can increase demands on existing governance arrangements, public infrastructure, and water-allocation mechanisms . Population growth is not an independent phenomenon and its impact may be magnified where institutions of urban planning, water-supply investment and resource management are not well-placed to respond to growing demand. The findings thus support the need to jointly consider the demographic pressures and institutional capacity in the assessment of the determinants of water stress.

The positive and statistically significant association between EPS and WSL provides another theoretical insight into the distinction between regulatory design and implementation effectiveness. Environmental policies may specify formal conservation objectives, but their intended benefits rely on adequate enforcement, institutional coordination and compliance. The observed relationship should not be taken as evidence that stricter environmental regulation necessarily aggravates water scarcity. Instead, it highlights the potential for lack of implementation, reactive policy responses, or measurement limitations to prevent regulatory stringency from bringing forth the expected environmental benefits. This reading emphasises the institutional dimension of the analysis by emphasising that environmental governance is a question of translating regulatory requirements into enforceable conservation measures in practice.

The insignificant long-run relationship between TO and WSL also challenges generalised interpretations of the Environmental Kuznets Curve (EKC). The results are inconclusive as to whether trade openness alone mitigates or aggravates water stress in Pakistan. Instead, they suggest that the environmental effects of economic integration may depend on the composition of trade, the resource intensity of domestic production and the effectiveness of environmental institutions. Thus, a shift to a more sustainable development path cannot be taken for granted as a consequence of rising incomes or greater economic openness. Thus, the theoretical contribution of the study is to highlight the interdependence of sectoral production, demographic pressures, institutional capacity and environmental constraints in explaining water stress in the economy of Pakistan.

The empirical results provide a basis for the development of a more integrated water-governance framework compatible with Sustainable Development Goal 6 (SDG 6), in particular its targets on sustainable management of water resources and efficient use of water resources. Due to the importance of agricultural output in explaining water stress, policy interventions should focus on modernisation of irrigation systems, gradual provision of subsidies for drip irrigation and wider adoption of context-appropriate water saving technologies. Such measures should be complemented with improvements in irrigation scheduling, water allocation and farmer awareness to translate technological adoption into measurable reductions in freshwater consumption. “We need to find ways of increasing agricultural productivity and at the same time using resources more efficiently not to put a complete stop to agricultural development.”

A complementary policy response is needed which focuses on urban planning, infrastructure development and sustainable freshwater provision, owing to demographic pressures. The growing population and urbanisation make it more important to coordinate the water-supply capacity with the expected demand, while improving the coordination between urban authorities and the water-allocation institutions. Resilient

water infrastructure investments, distribution infrastructure and demand management would reduce the strain on current water sources. Moreover, coordination between the provincial governments is needed to meet conflicting demands for water and to ensure the uniformity of water allocation and governance structures.

There is also a positive correlation between lagged FDI and WSL, which also calls for a more thorough consideration of the environmental effects of investment decisions. Water data should be considered transparently in investment screening and water-efficient technology and water management practices should be encouraged. Environmental safeguards should be commensurate with the nature of the investment and include regular monitoring, reporting and enforceable compliance standards. This would help to assure economic development with foreign investment, while not unduly stressing already limited freshwater availability.

Another key area is in strengthening the implementation of environmental policies. The positive value of EPS coefficient is a surprise, which implies that there is a need to differentiate between the presence of environmental regulations and the ability to implement them. Regulatory authorities should thus be provided with sufficient technical capacity, monitoring systems, a transparent enforcement and penalty system, and support. Greater coordination between federal and provincial institutions would further enhance implementation and minimize gaps and inconsistencies in water governance. In addition to, and where necessary, expanding formal regulations, policy makers should focus their efforts on ensuring effective enforcement of existing regulations and evaluating their effectiveness on a basis of measurable environmental outcomes.

Last, because the long run impact of TO is negligible, it is not safe to rely on economic openness as a guaranteed cause of environmental degradation or as a recipe for attaining sustainability. Instead, the assessment of trade and growth policies should be done together with the water demands of the sectors and investment structuring and regulatory capacity. A more credible basis for the advancement of SDG 6 would exist if an integrated policy framework that brings together agricultural modernisation, demographic planning, water-sensitive investment and effective environmental enforcement were developed. Pakistan thus needs to do more than just craft new policies; it needs to find institutional institutions that can put policies into practice and deliver tangible benefits in the way water is managed.

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