Groundwater dependent agricultural use and economic development: Does it show an EKC?

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Abstract

Groundwater management for agricultural use is crucial for ensuring sustainable agriculture and food security, especially in regions where water resources are scarce, such as Pakistan and India. This paper contributes to the current knowledge of the relationship between groundwater use for agriculture and economic development. This is the first study using the Environmental Kuznets Curve (EKC) framework to examine the global relationship between groundwater use and per capita GDP. The study uses the area equipped for irrigation by groundwater as the dependent variable and GDP per capita, and its quadratic term is used as the independent variable, along with some other factors included as control variables.

The empirical analysis commenced with a cross-sectional regression method, an appropriate econometrics technique due to missing values and time invariance constraints. Then, Panel Corrected Standard Errors (PCSEs) models were applied, which addressed issues such as heteroskedasticity (unequal error variances) and autocorrelation (correlation of error terms over time within each panel unit). Separate models were estimated with and without control variables and with and without lags of the explanatory variables for robustness checks.

All models consistently show that the area equipped for irrigation by groundwater initially increases with per capita GDP and decreases after reaching a certain income threshold. The observed inverted-U relationship between per capita GDP and groundwater use aligns with the EKC hypothesis. This suggests that countries tend to adopt more sustainable and efficient water management practices and technologies only after a certain level of wealth is reached. Advanced spatial technologies, including remote sensing and groundwater monitoring, while costly, could facilitate sustainable management of this critical resource.

Keywords: - groundwater management, agricultural sustainability, Environmental Kuznets Curve (EKC), per capita GDP, spatial technologies

1. Introduction

According to the World Health Organization and UNICEF, approximately 785 million people lacked access to basic drinking water facilities. In comparison, 2 billion people lived without basic sanitation facilities, as reported in 2017 (Swe *et al.*, 2021). More than 2 billion people in over 40 nations are concerned about water shortages (UNDP, 2006). Water, one of the most valuable resources in the world, is crucial for economic growth (Distefano & Kelly, 2017). The finite supply of fresh water and the exponentially rising demand for it threaten the integrity of the natural environment and human welfare. Therefore, accurately identifying current trends and predicting future developments for sustainable groundwater management using global data is essential.

Groundwater is an essential water resource, and it is highly ranked as strategically essential because of its increasing demand for industrial, irrigation, and household applications. According to a recent estimate, approximately 11% of the total non-renewable groundwater used for irrigation is also embedded in international trade food items. However, 70% of the total freshwater globally is utilized in agriculture, 25% in industry, and 5% in households (Dalin *et al.*, 2017).

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Groundwater is an essential natural resource that is the most important in fulfilling the demands of agricultural, industrial, and household demands. Agriculture is the top sector that consumes groundwater, which approximately utilizes 70% of the total groundwater withdrawals, especially in regions with water scarcity. Urban areas consume 15% of the total groundwater withdrawals. 10% accounts for industrial usage and 5% for households with global groundwater use (Bierkens & Wada, 2019), as shown in Figure 1.

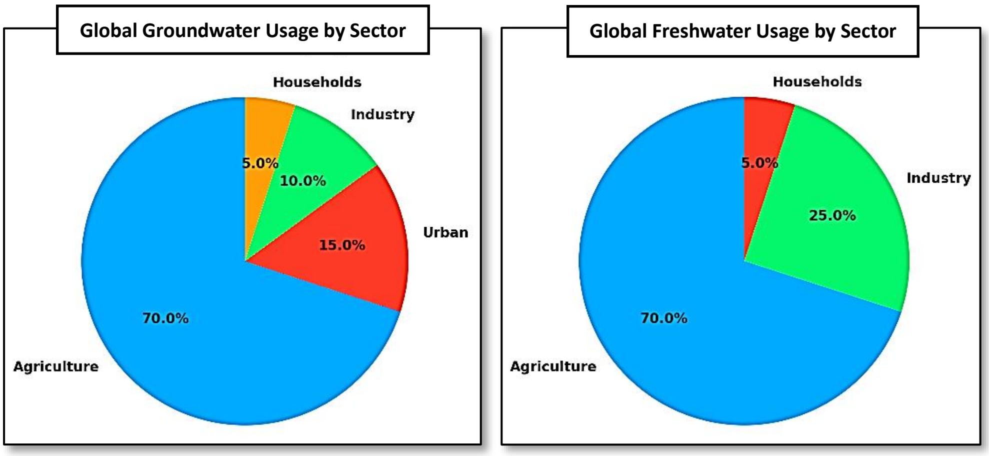


Figure 1. Comparison between Global Freshwater and Groundwater Withdrawals and Usage by Sector

Globally, groundwater storage capacity ranges between 750 and 800 km^3 per year, or around one-sixth of total freshwater abstraction (Mukherjee *et al.*, 2021), as shown in Figure 2. Compared with surface water worldwide, groundwater's contribution to agriculture is lower, but its specific benefits include efficiency, accessibility, availability on demand, fewer capital investments, and higher productivity (Shamsudduha *et al.*, 2022). Figure 2 compares groundwater storage capacity versus total freshwater abstraction globally.

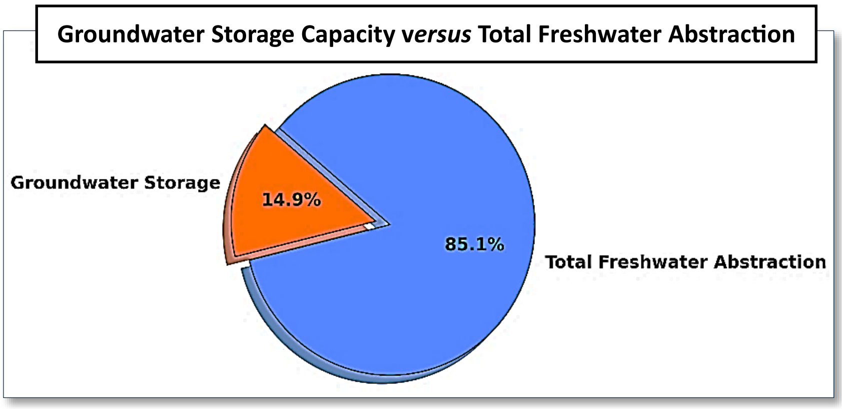


Figure 2. Groundwater Storage Capacity v*ersus* Total Freshwater Abstraction

According to an estimation, in 2024, groundwater accounted for between 21% and 30% of the total freshwater consumption at the global level, and this usage is continuously increasing due to the rapidly increasing population and its essential role in the water, food, and energy nexus (Loaiciga & Doh, 2024). However, the increasing demand driven by climate changes, population growth, and urbanization has led to remarkable groundwater withdrawal rates, and this extraction rate sometimes increases more than the replenishment rates in many regions (Green *et al*., 2011). This unsustainable extraction has resulted in groundwater depletion, connected with ecological and socioeconomic consequences such as land subsidence and the dropping rate of surface water bodies (Kumar *et al*., 2018).

Over-extraction globally, mainly driven by agricultural, industrial, and domestic/urban needs, is increasingly risking the sustainable management of groundwater resources (Sharma *et al*., 2021).

. Groundwater plays an essential role as a critical source of sustainable freshwater resources. However, the alarming rates of groundwater resources result in environmental consequences, which is a considerable cause for concern (Taylor *et al*., 2013). This situation becomes more complicated by the interaction of economic development and technological advancements in the agriculture sector, creating complex challenges in groundwater sustainability. The EKC framework suggests an inverted U-shaped relationship between economic growth and environmental degradation, and its practical implications for groundwater use and extraction vary regionally and are not straightforward (Bashir *et al.*, 2021).

This study aims to comprehensively investigate the relationship between groundwater use and extraction, exploring how these variables link with economic growth and the shape of the Environmental Kuznets Curve predicted in Figure 3.

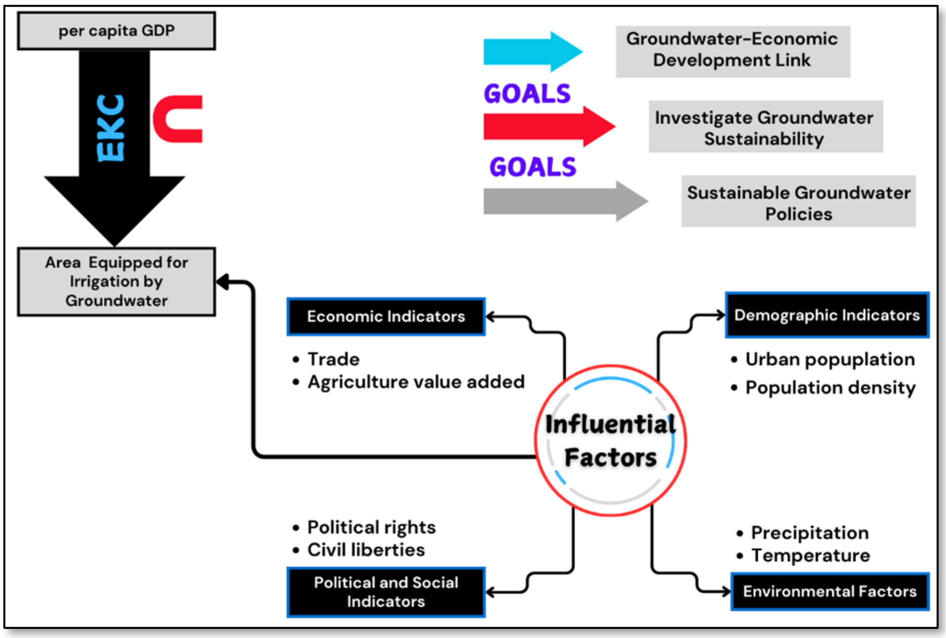


Figure 3. Research Model within the EKC Framework

The result of this research will provide practical implications for policymaking, especially in designing strategies for sustainable groundwater management in several regional and economic contexts.

2. Literature Review

The literature indicates that increased groundwater use is caused by increased per capita GDP due to higher demand for agricultural and industrial purposes. The agriculture sector contributes significantly to the country’s GDP, which influences the increase or decrease in water demand, and the agricultural sector's water needs determine the groundwater withdrawal volume (Siebert *et al*., 2010). Increasing urban population trends increase the pressure on groundwater resources, which ultimately promotes effective water sustainability policies to prevent the over-extraction of groundwater (Wada *et al*., 2010). Furthermore, the role of trade in agriculture production causes significant groundwater depletion, especially in the case of water-intensive crops (Dalin *et al*., 2017).

Moreover, population density also impacts groundwater withdrawal, which is related to more heavily populated areas typically having higher rates of groundwater use (McDonald *et al*., 2011). Climate-related indicators like precipitation and temperature are critical in determining the natural renewal of aquifers and additional water demand for irrigation, which ultimately influence groundwater withdrawal rates (Taylor *et al*., 2013). Lastly, the governance framework combines political rights and civil liberties, which are the instruments for regulating groundwater use and ensuring sustainable groundwater extraction practices (Khara, 2023).

Bierkens & Wada (2019) state that population growth and economic development significantly impact fresh groundwater withdrawal. As the population and economies grow, there is an increase in demand for food and water. This will cause an expansion in agricultural activities, especially in semi-arid areas with water scarcity, limited rainfall/precipitation, and surface water availability. As a result, these areas are heavily dependent on groundwater resources for agricultural practices. In addition, with the expansion of urbanization, the demand for groundwater is increasing.

Fahle & Dietrich (2014) focus on the significance of the interaction between groundwater and surface water, especially in wetlands. Plants in specific areas fulfill their water needs from underground water layers above the groundwater; this activity of plants taking water causes the groundwater level to go down daily. Understanding these interactions is crucial for estimating daily groundwater evapotranspiration rates and assessing recharge assumptions.

The area equipped for power irrigation is an essential indicator that plays a role in meeting the growing water needs of agricultural productivity. According to Kumar *et al*. (2023), power irrigation indicates the inclusion of technological integration in agricultural practices to increase crop productivity while conserving water.

Moreover, Valipour (2017) investigates an in-depth estimate of the area equipped for power irrigation globally, which is likely to undergo substantial changes between 2035 and 2060. This study focuses on the role of several indexes, such as the human development index and rainfall index at the national level, which determines the irrigation requirements. In addition, the research reports a thorough global inventory of areas irrigated with different water resources. The area equipped for irrigation is approximately 301 million hectares, of which approximately 38 percent is equipped for irrigation with groundwater.

Furthermore, Meier *et al*. (2018) predict the challenges in planning irrigated areas by comparing global groundwater datasets. This study represents a more extensive area irrigated by groundwater than the previous research shows, with the vast difference observed in China and India. Similarly, Qin *et al*. (2019) indicate a closer picture of the past and current trends in global irrigation growth. This research is crucial in understanding the accurate scale of the area equipped for power irrigation in the agriculture sector, which plays a role in correcting the increased percentage and providing a more reliable basis for future estimation.

The study by Valipour (2017) analyzes global water management under various scenarios. This research highlights the understanding of pressure on renewable water resources due to increasing irrigation and emphasizes the importance of requirement-based future planning. It also highlights the increasing trend and critical factors affecting the area equipped for power irrigation and suggests practical strategies for managing these changes.

Neumann *et al*. (2011) employ a comprehensive analytical framework to explore global irrigation patterns. The study focuses on understanding the biophysical, socioeconomic, and governance determinants that shape these patterns. Their study is crucial for identifying areas where irrigation expansion is likely and emphasizes the importance of considering a range of factors to understand global irrigation trends. This approach sheds light on the complex nature of irrigation expansion, revealing the need to integrate various types of information in irrigation planning.

Siebert *et al*. (2010) investigate global irrigation patterns and multilevel modeling methods focusing on socioeconomic and government policy frameworks. This study is essential in identifying the areas where irrigation expansion is expected and focuses on the significance of considering several factors to understand global irrigation practices. According to Famiglietti *et al*. (2011), satellite data was utilized to investigate the alarming rate of groundwater depletion in California's Central Valley, a well-known region for agricultural practices. This study comprehensively analyzes the groundwater sustainability challenges caused by excessive groundwater extraction rates. These findings highlight the critical need for developing sustainable water management strategies and policies to mitigate groundwater increased depletion.

Dangar *et al*. (2021) examine the critical role of groundwater in India's food security and economic growth. This study focuses on the irrigation which is groundwater-based irrigation, which causes an increase in agricultural productivity but, consequently, is the cause of groundwater depletion. This study highlighted irrigation through groundwater and its sustainability in long-term agriculture practices, especially in developing regions. Duncan *et* *al*. (2008) review the processes and management strategies related to salt mobilization in irrigation areas. They note that salt mobilization varies between regions and is influenced by factors like hydrogeological setting, irrigation management, and climatic trends. This study underscores the importance of considering environmental factors in managing irrigation systems. Singh (2014) presents an overview of the conjunctive use of surface and groundwater resources for sustainable irrigated agriculture. This approach allows the utilization of poor-quality water and addresses issues like rising water tables. The paper discusses computer-based models for managing conjunctive water use, highlighting the necessity of integrating different water sources for sustainable agriculture. This indicates the complex relationship between climatic conditions and groundwater resources in irrigation management. Ajaz *et al*. (2020) discuss groundwater depletion in the USA's High Plains Aquifer (HPA), mainly irrigated agriculture. The study highlights the imbalance between recharge and extraction, stressing the need for better management approaches like deficit irrigation and soil moisture sensors to enhance the sustainability of groundwater use in agriculture. Pereira *et al*. (2015) review the FAO56 framework for crop evapotranspiration, which is crucial for computing water requirements in irrigation. The paper discusses advancements in computing reference evapotranspiration and estimating crop coefficients under different environmental conditions. This highlights the importance of precise water requirement calculations in irrigation planning. Per capita GDP indicates the nation's financial growth to implement advanced irrigation technologies. Previously, Smith & Siciliano (2015) have described the connection between economic measures and the ability to invest in agricultural innovation. Complementarily, demonstrates that wealthier nations allocate more resources to power irrigation, linking economic health to technological uptake (Burney & Naylor, 2012).

The percentage of GDP originating from agriculture is often regarded as a forecast for investment in irrigation technology (Siebert *et al*., 2010). This economic marker indicates a country's propensity to enhance crop productivity by developing power irrigation systems.

In investigating the impacts of per capita GDP on groundwater use and extraction, this research delves into how a country's economic status, reflected in its per capita GDP, correlates with its groundwater consumption and extraction trends. Per capita GDP, a standard measure of average income, offers insights into the economic activities of a nation, particularly within its industrial and agricultural sectors, and how these activities drive groundwater demand. The study aims to solve the complex link between a nation's economic condition and the pressure it places on groundwater resources, focusing on the balance between economic development and groundwater sustainability. This relationship is critical in understanding the broader implications of economic growth on environmental sustainability and resource management (Fedulova *et al*., 2021)

On the other hand, GNI (gross national income) includes domestic production income and remittances from abroad. GNI includes elements that do not directly influence groundwater use and extractors, such as foreign savings and remittances.

This study focuses on the association of per capita GDP with groundwater use per person. Moreover, extraction because the domestic economy, like per capita GDP, directly impacts groundwater use and extraction. Incorporating gross national product could involve indicators that might not directly influence a country’s internal groundwater use, which can cause theoretical weakness and possibly introduce biased study findings.

Urban population size is a metric that reflects the growing demands placed on agricultural output (Wang *et al*., 2021). Urbanization is often cited as a driver for increased agricultural production, which often requires adopting efficient irrigation methods like power irrigation to

keep pace with demand. Trade policy's impact on agricultural development can be viewed as an incentive meter that motivates the adoption of efficient irrigation technologies, an investment necessary to increase productivity and meet international standards.
Population density often indicates the pressure exerted on land and water resources. This demographic challenge catalyzes the adoption of technologies that ensure efficient water use, such as power irrigation, to maximize the yield per hectare of arable land. Rainfall patterns are a critical metric for determining the necessity of power irrigation systems. Precipitation necessitates the development of irrigation systems that can draw on various water sources, including groundwater and rivers, to provide a reliable supply for crops (Chen *et al*., 2020).

Temperature profiles signal the increased water needs of agricultural systems, especially in areas with high evapotranspiration rates. Regions experiencing higher temperatures are typically more equipped with power irrigation systems to address these heightened demands for water. The governance structure offers a way to assess the agricultural technological advancements within a country. Political freedoms are essential to a country's capacity to implement and scale up power irrigation systems, as described in recent studies that focus on policy frameworks and governance to advance irrigation sustainability (Alaerts, 2020).

3. Data and methods

3.1 Data

As outlined above, water usage may be influenced by per capita GDP. Given that water is a standard product, positive income elasticity of demand for domestic use would mean that consumption increases as income rises. Increases in wealth also make it possible to access marginal water sources that were previously inaccessible at low-income levels (such as water treatment, deep aquifer pumping, etc.). On the other hand, higher income may lead to less water usage. It may enable more water-saving technology (like drip irrigation) and better water delivery system maintenance, leading to lower water loss levels via leaks. Additionally, nations may gradually transition away from agriculture, the most significant water consumption sector, and towards less water-intensive industries like services. However, the proportional magnitude of these impacts and, hence, the total influence of income on water usage have yet to be explored well so that no prior assumptions can be made.

There is much research on the income elasticity of household water demand, but only some have looked at the relationship between total water usage and per capita GDP. The majority of these have discovered an inverted-U-shaped EKC. Gleick (2003a) found no evidence of a connection between per capita national water withdrawals and income. Rock (1998) conducted the first research to identify an EKC for water withdrawals and looked at cross-sectional data for worldwide withdrawals and panel data for withdrawals at the state level in the United States. Rock's study is innovative but has several limitations. The study based on the Environmental Kuznets Curve for water withdrawal is highly dependent on cross-sectional data sets, which may need to be more accurate to accurately predict the complexities of water usage patterns. In addition, the choice of methodology needs to be more accurate in the relationship between economic growth and water usage patterns. Many studies have examined the EKC regarding groundwater use in agriculture.

Groundwater is a primary source of irrigation in many regions worldwide. Thus, the area equipped for groundwater irrigation can offer insights into agricultural practices. Such monitoring can assist policymakers in understanding the dependency on groundwater for irrigation, ultimately promoting planning strategies for its sustainable use (Siebert *et al*., 2010).

Per capita GDP (constant 2017 international $) indicates economic prosperity and can influence water consumption patterns. Regions with higher per capita GDP often have better infrastructure, efficient water extraction technology, and firm policies. Furthermore, per capita GDP can drive changes in agricultural practices, potentially changing water demand (Li *et al*., 2021). On the economic front, agriculture's value-added (% of GDP) indicates the economic importance of the agriculture sector. Countries where agriculture contributes significantly to GDP show different water consumption patterns. Therefore, policymakers in these countries can prioritize efficient irrigation systems and sustainable water management practices (Velasco Muñoz *et al*., 2022).

Urban areas typically demonstrate different water consumption patterns compared to rural areas. As urban populations grow, water demand for domestic and industrial purposes rises, impacting water availability for agriculture (McDonald *et al*., 2011).

From a trade perspective, a country's trade patterns can shape its water consumption. Exporting water-intensive goods, or "virtual water trade," effectively exports water, while importing such goods can decrease domestic water demand. Understanding trade's contribution to GDP can offer policymakers insights into a country's virtual water trade practices (Hoekstra & Mekonnen, 2012). Demographically, high population density can exert significant pressure on local water resources. Highly populated areas may require strict water management practices to ensure sustainable supply and meet the population's needs (Chen *et al*., 2020).

Furthermore, precipitation and temperature directly impact water consumption. Regions with low precipitation often rely more on groundwater for agriculture, while temperature variations affect evaporation rates and crop water management. Thus, monitoring these factors is essential for sustainable groundwater management (Niles *et al*., 2018). The amount of precipitation that falls on average each year (precipitation). To capture climatic regional variations, especially regarding water resources, since water shortage is often a regional issue. This variable is supported by the observation that regions with more water shortage tend to use their resources better (Zareian, 2021).

So, it is estimated that the varied precipitation would exhibit a good trend. Second, some scholars emphasize how environmental management varies among nations based on political and socioeconomic circumstances.

Some argue that improving democracy entails improving environmental performance and, consequently, reducing natural resource use and environmental damage (Toigo & de Mattos, 2021).

Therefore, we try to control for institutional differences by adding a variable called political freedom (PF). Based on the information provided by Freedom House, we use this qualitative variable ranging from 1, representing the most politically free, to 7, the least politically free. According to Duarte *et al*. (2013), PF is expected to display a positive coefficient; the higher the PF index or the less politically free a country is, the more water per capita is withdrawn.

The descriptions for the explanatory, control, and dependent variables and download sources are provided in Table 1.

Table 1. Variable description

Abbreviation	Indicators	Unit	Data Source	Variable Definition
Dependent Variables				
AEIG	Area equipped for irrigation by groundwater	1000 hectares	FAO AQUASTAT	Refers to the total area in hectares equipped for irrigation by groundwater.
Per capita GDP	per capita GDP, PPP adjusted	US dollars	World Bank Data	per capita GDP based on PPP is the gross domestic product converted to international dollars using PPP rates.
Control Variables				
Aggdp	Agriculture, value added	%	FAO AQUASTAT	Agriculture value added (% GDP) measures the agricultural sector's contribution to GDP.
Upopulation	Urban population	% of total Population	World Bank Data	Urban population refers to people living in urban areas defined by national statistical offices.
Tradegdp	Trade	%	World Bank Data	Trade is the sum of exports and imports of goods and services measured as a share of GDP.
Populatden	Population density	people per sq. km	World Bank Data	Population density is the mid-year population divided by land area in square kilometres.
Prec	Precipitation	mm/year	Climate Change Knowledge Portal	Average precipitation is the country's long-term average in depth of annual precipitation.
Temp	Temperature	Celsius	Climate Change Knowledge Portal	Temperature refers to the measure of how hot or cold the environment is.
PR	Political rights	Rank[1,2]	Freedom House	Political rights refer to participating in civil and political life without discrimination.
CL	Civil liberties	Rank	Freedom House	Civil liberties are the fundamental rights and freedoms that individuals should have.

3.2 Methods

The analysis started with properly handling missing data and checking the dataset for time-invariant behaviour of proposed variables to ensure the robustness of cross-sectional regression. Due to the data limitation and time-invariant behaviour of our selected variables, the cross-sectional regression technique was selected because it is the most appropriate technique for getting consistent results in case of data limitations.

[1] https://freedomhouse.org

[2] Until 2003, PR and CL between 1.0 and 2.5 were designated Free; between 3.0 and 5.5 were Partially Free, and between 5.5 and 7.0 were Not Free. After 2003, 3.0 and 5.0 were Partially Free, and those between 5.5 and 7.0 were Not Free.

This study has a logarithmic transformation of dependent and independent that is expressed in continuous form (Smith, 1993). This conversion was necessary to address issues like non-linearity and reduce skewness, facilitating more meaningful regression coefficients.

Initially, the relationship between per capita GDP and water usage was examined without control variables to observe the direct influence of GDP on dependent variables. At the later stage, control variables were introduced to analyze how additional factors influence this relationship. Such a methodological procedure enhances the thoroughness of estimating the primary impact of both control and explanatory variables on the dependent variables.

The equation representing the cross-sectional between effect estimator without control variables is as follows:

$$LAEIG_i = \alpha + \beta 1 Lgdpcapita_i + \beta 2 (Lgdpcapita_i)^2 + \epsilon_i \qquad (1)$$

This model signifies cross-sectional regression between effects LAEIG indicates a dependent variable. In contrast, for the countries included in the dataset, α shows intercept, and the coefficients of per capita GDP and per capita GDP-squared indicate a quadratic relationship; adding a quadratic term is trying to capture the potential nonlinear relationship indicating in the EKC showing that per capita GDP has a nonlinear impact on groundwater use and extraction. While ϵ is is an error term that shows unobserved influences on the dependent variable outcome.

The equation representing the cross-sectional between the effect estimator and control variables is as follows:

$$LAEIG_i = \alpha + \beta 1 Lgdpcapita_i + \beta 2 (Lgdpcapita_i)^2 + \gamma Z_i + \epsilon_i \qquad (2)$$

Each control variable in Zi gamma (γ) is the vector of coefficients for the control variables it will have its coefficient, which measures the influence of other factors on LAEIG (dependent variable).

To ensure stationarity, we conducted preliminary checks before running the panel regression. We commenced with a Fisher-type unit root test to confirm the stationarity of the data.

$$FCPS_{LAEIG} = -2\sum_{i=1}^{N} \log(pLAEIG_i) \tag{3}$$

$$FCPS_{Lgdpcapita} = -2\sum_{i=1}^{N} \log(pLgdpcapita_i) \tag{4}$$

The Fisher-type unit root test statistic (Fisher combined p-statistic) is given by combining p-values (*pi*) from individual unit root tests across *N* panels in a dataset. Each *pi* is the p-value from the unit root test of the *i*-th panel (each country is the i-th panel). The test statistic follows a chi-square ($\chi 2$) distribution with 2*N* degrees of freedom. In this formula, the natural logarithm of each p-value is taken and multiplied by -2. The sum of these transformed values signifies the Fisher test statistic. A higher value of this statistic suggests stronger evidence against the null hypothesis, which typically posits the presence of a unit root (non-stationarity) in all panels. The test was applied separately on the dependent area equipped for irrigation by groundwater (LAEIG) and the independent variable per capita GDP (Lgdpcapita). The results have been presented in Appendix A.

Our findings allowed us to confidently reject the null hypothesis of a unit root in the panel dataset. After applying the panel-corrected standard error model, we incorporated lagged variables to control for and mitigate the potential reverse causality flowing from the dependent to the explanatory and control variables.

First, the following simple model is considered:

$$LAEIG_{it} = \alpha + \beta 1 Lgdpcapita_{i,t} + \beta 2\left(Lgdpcapita_{i,t}\right)^2 + u_{it} \quad (5)$$

The panel model is estimated via the Panel Corrected Standard Errors (PCSE) approach. PCSE is a useful method in panel data analysis to tackle issues like heteroskedasticity, which refers to unequal error variances, and autocorrelation, meaning the correlation of error terms over time within each panel unit (Beck & Katz, 1995). By applying PCSE, more accurate standard error can be estimated, a crucial factor for ensuring reliable statistical testing in panel studies. We note that PCSE is used in the above simple model setting and the following extended models. However, it is also worth noting that PCSE operates under the assumption that error terms are not correlated across different units in the panel, which can be a limitation in some analyses (Beck & Katz, 1995).

In addition to the simple model, a batch of extended models are considered. First, a vector of control variables is included:

$$LAEIG_{it} = \alpha + \beta 1 Lgdpcapita_{it} + \beta 2(Lgdpcapita_{it})^2 + \gamma Z_{it} + u_{it} \quad (6)$$

Since the effect of income on groundwater may not occur immediately, panels with lagged independent variables are specified as follows:

$$LAEIG_{it} = \alpha + \beta 1 Lgdpcapita_{i,t-1} + \beta 2(Lgdpcapita_{i,t-1})^2 + \gamma Z_{it-1} + u_{it} \quad (7)$$

We next extend Models (5)-(7) to incorporate the country fixed effects (FE), v_i. With FE, the estimation can be ease of bias due to time-invariant omitted variables. Specifically, the models are presented in Models (8)-(11).

The equation representing the PCSE without control variables with country fixed effect:

$$LAEIG_{it} = \alpha + \beta 1 Lgdcapita_{it} + \beta 2 (Lgdpcapita_{it})^2 + v_i + u_{it} \quad (8)$$

The equation representing the PCSE with control variables with country fixed effect:

$$LAEIG_{it} = \alpha + \beta 1 gpcapita_{it} + \beta 2 (Lgdpcapita_{it})^2 + \gamma Z_{it} + v_i + u_{it} \quad (9)$$

The equation representing the PCSE with lagged control variables with country fixed effect:

$$LAEIG_{it} = \alpha + \beta 1 Lgdpcapita_{i,t-1} + \beta 2 (Lgdpcapita_{i,t-1})^2 + v_i + u_{it} \quad (10)$$

The model represents the panel corrected the standard error with control with lag with country fixed effect:

$$LAEIG_{it} = \alpha + \beta 1 Lgdpcapita_{i,t-1} + \beta 2 (Lgdpcapita_{i,t-1})^2 + \gamma Z_{it-1} + v_i + u_{it} \quad (11)$$

Table 2. Model Specifications: Controls, Lags, and Country Fixed Effects

Modelling Approach		**Control Variables**			
	Model Specification	**Without Control Variables**		**With Control Variables**	
		Lag		Lag	
		with lag	without lag	with lag	without lag
Country Fixed Effect	with control variables			X	
	without control variables			X	

Author's Computation

Table 2 summarizes the model specifications for control variables, incorporating lags and country-fixed effects in the statistical analysis procedure. The models are applied in two ways: the first is the base model without any control variables, and the second is with control variables. The first column indicates models without control variables, with no lagged or country-fixed effects applied. On the other hand, the second column defines models with control variables. In the case of models with control variables, lagged variables, and country-fixed effects are applied. The indication of "X" shows that models with and without control variables, with lags, and with country-fixed effects are the best models that predict an inverted U-shaped EKC.

4. Results

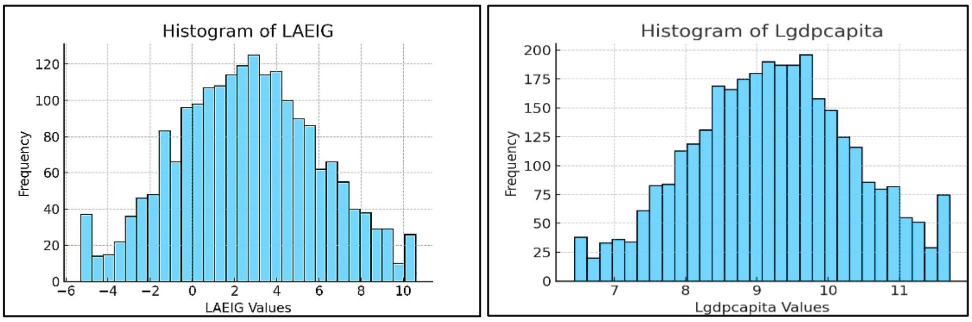
4.1 Descriptive statistics

Table 3 presents the descriptive statistics for a whole dataset as the area equipped for irrigation by groundwater in 1000 ha; the log shows an average of 2.6 with a standard deviation of 3.49, indicating that the area equipped for irrigation by groundwater in hectares shows considerable variability in the areas equipped for irrigation by groundwater within -5.21-10.58. Meanwhile, population density averages 187.106 with a high standard deviation of 578.43, indicating extreme variation from 1.58 to 7965.88. Trade (% of GDP) reveals that the average trade-to-GDP ratio is 87.3, with values stretching from 11.85 to 437.32, indicating economic trade openness across different regions. Precipitation and temperature cover environmental aspects with an average precipitation of 1278.23 mm and mean temperature at 19.69°C, indicating a broad range of 21.97 to 5,388.9 mm and -4.94 to 29.75°C, respectively. This highlights diverse climate conditions from dry to wet and cold to warm (% of GDP) is agriculture share, and the value-added percentage of GDP shows an average of 12.44 with a range of .03 to 79.69, pointing out the growth rates across datasets. Per capita GDP and per capita GDP square provide an understanding of economic prosperity with mean values of 9.17 and 18.35 and ranges of 6.44 to 11.70 and 12.89 to 23.40, indicating a wide disparity in income level.

Table 3. Summary Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Area equipped for irrigation by groundwater (1000 ha, log, AEIG)	1995	2.6	3.49	-5.21	10.58
Per capita GDP (log)	3207	9.17	1.17	6.44	11.70
Population density (people per sq. km, log)	3340	4.23	1.39	.46	8.98
Trade (% of GDP)	2971	87.3	51.18	11.85	437.32
Political rights	3340	3.29	2.13	1	7
Civil liberties	3340	3.24	1.82	1	7
Agriculture share (% of GDP)	3340	12.44	12.22	.03	79.69
Urban population (% of total population)	3340	55.51	22.822	8.246	100
Temperature (Celsius, log)	3298	2.87	.51	-1.51	3.39
Precipitation (mm/year, log)	3320	6.85	.88	3.09	8.59

However, political rights and civil liberties are related to political freedom, having means of 3.29 and 3.24 and rank/range from 1 to 7, reflecting stability in political rights and civil liberties globally. Figure 4 shows the graphical representation of the area equipped for irrigation by groundwater(log) and per capita GDP (log) in histograms.



area equipped for irrigation by groundwater (hectares, log)

gross domestic product per capita (US$, log)

Figure 4. Graphical Representation of Summary Statistics of Selected Variables

4.2 Cross-sectional between-effect model with and without control variables

The cross-sectional between-effect estimator focuses on differences between such countries by considering the average value of each country over time. This approach highlights how variables affect these entities differently but does not consider these changes with each entity over time. It is a practical approach for understanding entity variations but less for analyzing trends within each entity over time. The results from the cross-sectional models with and without control variables are presented.

Table 4. Cross-sectional between-effect model without control variable

Variables	Model 1	Model 2
Per capita GDP (log)	14.89***	10.16**
	(4.24)	(4.54)
Per capita GDP (log) square	-0.78***	-0.53**
	(0.23)	(0.24)
Agriculture share (% of GDP)		-0.03
		(0.05)
Population density		0.59**
		(0.25)
Urban population		0.03
		(0.02)
Precipitation (log)		-0.67*
		(0.37)
Temperature (log)		-0.63
		(0.51)
Trade (% of GDP)		-0.03***
		(0.01)
Political rights		0.20
		(0.18)
Constant	-67.22***	-39.95*
	(18.95)	(21.18)
Observations	1,870	1,704
R-squared	0.17	0.44
Number of countries	99	92

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Model 1 in Table 4 indicates the existence of an inverted U-shaped EKC. For instance, the model shows that the coefficient of per capita GDP (log) is 14.89, which is a positive coefficient, and the coefficient of the squared term of the per capita GDP square(log) is -0.78, which is negative; both are significant at 1% level. Therefore, when income rises, the area equipped for irrigation by groundwater follows an increasing trend. When income reaches approximately 13766 USD, it is a turning point of decrease in the area equipped by groundwater but with a slower rate, which modelled an inverted U-shaped EKC curve. Similarly, model 2 in table 4 results from cross-sectional models with control variables shows the patterns of LAEIG, which shows an inverted U-shaped curve, as shown in Figure 5.

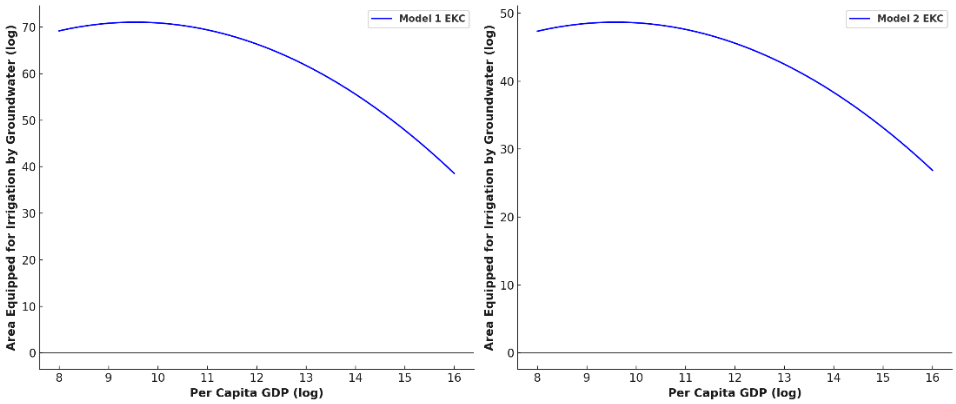


Figure 5. Inverted U-shaped EKC for all Cross-Sectional between-effect Models: Per Capita GDP, Area Equipped for Irrigation by Groundwater with & without Controls Variables

This means that if the per capita GDP goes up, the area equipped by groundwater and fresh groundwater use will first increase and then decline.

4.3 Panel Corrected Standard Error Models with and without control, fixed effect, lag

The following table demonstrates the results from panel-corrected standard error models. Acknowledging the crucial role of these corrections in panel data analysis is essential. The intention is to apply the panel-corrected standard errors to address issues such as heteroscedasticity and serial correlation, enhancing the statistical accuracy of the tested models. The models consistently show the presence of an EKC.

Table 5. Panel Corrected Standard Error Models with and without control, fixed effect, lag

Panel Corrected Standard Error Models	Model 3 (No Control)	Model 4 (With Control)	Model 5 (No Control,	Model 6 (With Control,	Model 7 (No Control,	Model 8 (With Control,	Model 9 (No Control,	Model 10 (With Control,
			Lag		Country Fixed Effect		Lag & Country Fixed Effect	
Per capita GDP (log)	3.85***	8.01***				0.71***		
	(0.71)	(0.91)				(0.27)		
Per capita GDP (log, t-1)			3.89***	7.92***	0.58***		0.53***	0.57**
			(0.86)	(0.97)	(0.19)		(0.20)	(0.24)
Per capita GDP (log) square	-0.19***	-0.43***				-0.05***		
	(0.04)	(0.05)				(0.02)		
Per capita GDP (log, t-1) square			-0.11***	-0.43***	-0.03***		-0.03**	-0.04***
			(0.05)	(0.05)	(0.01)		(0.01)	(0.01)
Agriculture share (% of GDP)		-0.00				0.00***		
		(0.00)				(0.00)		
Agriculture share (% of GDP, t-1)				-0.00				0.00
				(0.00)				(0.00)
Population density (log)		0.19***				-0.07		
		(0.05)				(0.04)		
Population density (log, t-1)				0.00**				0.00***
				(0.00)				(3.66)
Urban population		0.04***				0.01***		
		(0.00)				(0.00)		
Urban population (t-1)				0.03***				0.01***
				(0.00)				(0.00)
Precipitation (log)		-0.10***				0.00		
		(0.03)				(0.00)		
Precipitation (log, t-1)				-0.10***				-0.01
				(0.03)				(0.01)
Temperature (log)		-0.11***				0.00		
		(0.04)				(0.01)		
Temperature (log, t-1)				-0.083**				-0.00
				(0.03)				(0.01)
Trade (% of GDP)		-0.01***				0.00***		
		(0.00)				(0.00)		
Trade (% of GDP, t-1)				-0.01***				0.00***
				(0.00)				(0.00)
Political rights		0.02				0.00		
		(0.02)				(0.00)		
Political rights (t-1)				0.026				0.00
				(0.02)				(0.00)
Constant	-16.19***	-34.73***	-16.40***	-33.65***	3.99***	-2.94***	4.25***	0.03
	(3.64)	(4.15)	(3.965)	(4.38)	(0.77)	(1.01)	(0.71)	(1.01)
Country Fixed Effect					Yes	Yes	Yes	Yes
Observations	1,870	1,704	1,792	1,632	1,870	1,704	1,792	1,632
R-squared	0.25	0.32	0.25	0.32	0.99	0.99	0.99	0.99
Number of countries	99	92	99	92	99	92	99	92

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Model 10 in Table 5 is the most comprehensive model controlling for lags and country-fixed effects. The model shows that the area equipped for groundwater irrigation has a significant relationship with per capita GDP. The lagged coefficient of per capita GDP (log, t-1) appears positive and significant at 5%. The lag parameter of the per capita GDP square (log, t-1) is negative and significant at 1%. Its value is small, reaching -0.04. According to these empirical results, the area equipped for irrigation by groundwater seems to follow a growing trend with a steep slope for low-income values. As income rises, the slope becomes flatter until the log of per capita GDP 6.92 is reached and beyond, where LAEIG starts to fall as income increases. The inverted-U relationship implied by the modelling outcome is often called the EKC. Moreover, the estimated coefficients of lagged population density, urban population, and trade are all positive and significant at a 1% level, indicating that when each of these indicators increases, the area equipped for irrigation tends to rise, as predicted in Figure 6.

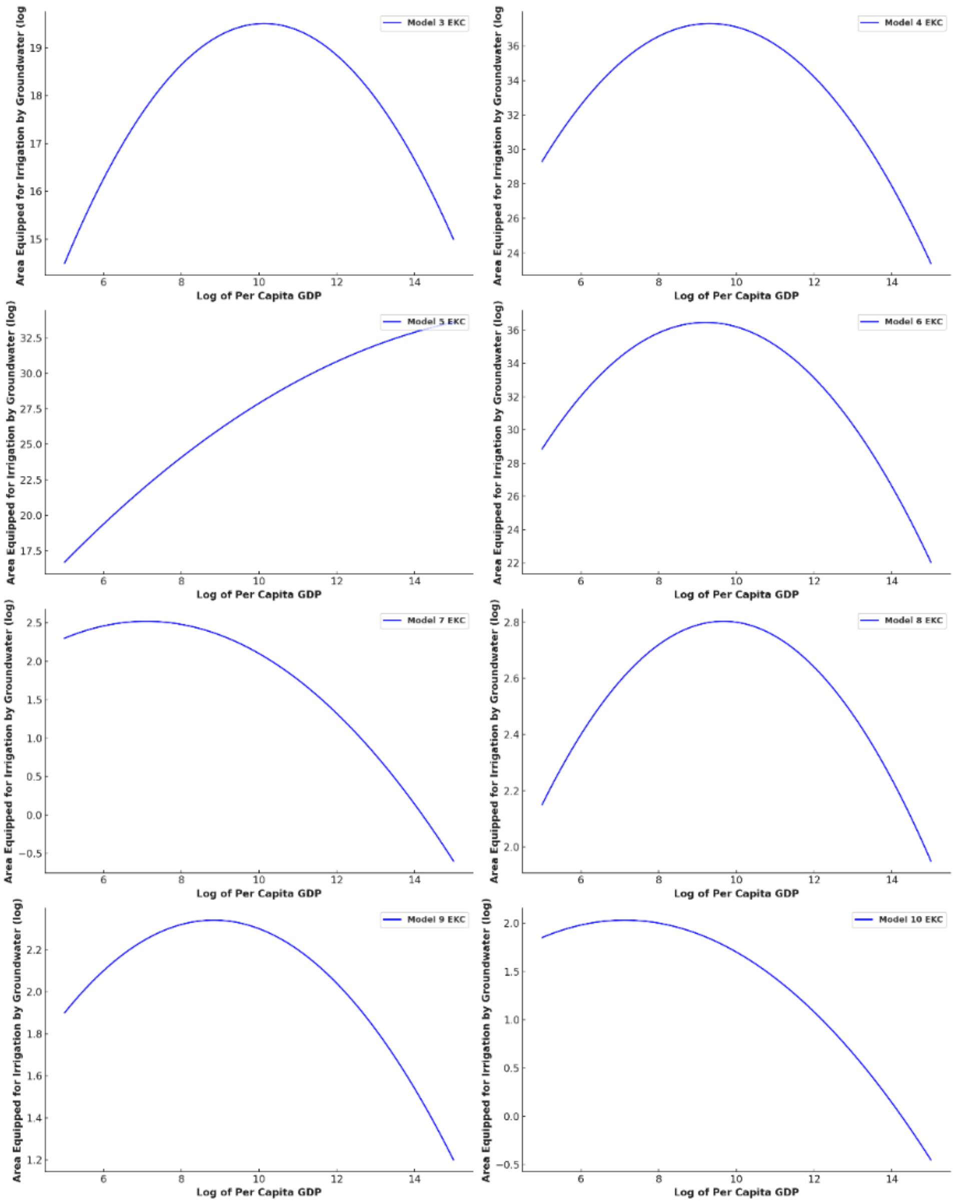


Figure6. Inverted U-Shaped EKC for all Panel Models: Per Capita GDP, Area Equipped for Irrigation by Groundwater with & without Controls with Country Fixed Effects & with Lags

Models 3 – 10 consistently show an inverted U-shaped Environmental Kuznets Curve (EKC) trend.

5. Discussion

This study supports the Environmental Kuznets Curve hypothesis regarding the relationship between per capita GDP and groundwater use. The results show that the area equipped for irrigation increases if the per capita GDP increases until a certain income threshold, and after a specific income threshold level, it starts to decline.

This pattern aligns with Duarte *et al*. (2013) findings, which illustrate the Environmental Kuznets Curve hypothesis in various contexts. In many developing countries, economic growth is initially the cause of natural resource exploitation, including groundwater for irrigation purposes. However, when incomes reach a higher level, groundwater use shifts towards more sustainable groundwater management for agricultural use. This shift reflects an inverted u-shaped Environmental Kuznets Curve, where groundwater use increases per capita GDP but later declines with adopting sustainable practices (Duarte *et al*., 2013).

The environmental implications of this study finding are significant. Initially, per capita GDP increases the demand for water to enhance agricultural productivity and increase the area equipped for irrigation by groundwater, causing higher groundwater extraction rates. This trend is followed primarily in the regions where the agriculture sector plays a vital role in the increase or decrease of per capita GDP and where huge populations rely on the agriculture sector regarding their incomes. The over-extraction of groundwater is linked with severe environmental degradation, i.e., land subsidence and depletion of aquifers. Kumar *et al*. (2018) highlight that this kind of depletion and environmental degradation causes a reduction in water availability and worsens soil salinity, which intensively impacts crop yields. This situation further deteriorated because of the requirement for higher energy to pump water from a deeper level, ultimately raising the irrigation cost. So, these consequences only threaten long-term agricultural practices, emphasizing the need for sustainable groundwater practices.

Economically, the shifting trend from initially increased to decreased areas equipped for irrigation by groundwater at a higher level of per capita GDP is handled by adopting technology for more efficient use of groundwater and sustainable groundwater management. In developed countries, the trend is to invest in advanced technologies that reduce groundwater use and the efficient use of water, saving water from wastage with the continued increase in per capita GDP. Valipour (2017) discussed that the shift towards reducing groundwater use is essential for sustainable water management practices, allowing economic growth to continue without natural resource degradation. This study investigates the importance of advanced irrigation technologies for water use in an efficient manner supported by the regulatory policy framework. These regulatory policy frameworks and advanced irrigation technologies shifts align with the trends in sustainable development, ensuring that economic growth can continue while maximizing environmental impacts.

6. Conclusion

The findings of this study significantly contribute to the discourse on groundwater management, particularly in the context of the Environmental Kuznets Curve (EKC) theory. It empirically tests the Environmental Kuznets Curve theory in groundwater sustainability. It illustrates how per capita GDP increases initially and groundwater use increases. However, groundwater usage declines when per capita GDP reaches a specific point, proving the inverted U-shaped EKC theory. This provides an essential understanding of economic factors' role in sustainable groundwater management. The finding of this research is that when per capita GDP increases, the area equipped for irrigation also increases, but after reaching income at a certain level, the trend reverses. As a result, the observed inverted-U relationship between per capita GDP and groundwater use aligns with the EKC hypothesis, which suggests that environmental degradation initially increases with economic development but decreases after reaching a certain income level (He *et al*., 2022). This pattern is evident in our results, where the area equipped for irrigation by groundwater initially grows with rising per capita GDP but starts to decline beyond a specific income threshold. This suggests that countries may invest more in sustainable and efficient water management practices at higher income levels, corroborating findings from previous research (Pereira & Marques, 2021).

This could be attributed to the increasing demand for agricultural products due to urbanization and global trade, as evidenced by our models' positive coefficients for population density, urban population, and trade. The perceptions emphasize the importance of economic growth factors in environmental conservation policymaking. The role of per capita GDP is significant in explaining groundwater management strategies, especially in developing countries where the trend is to utilize unsustainable resources with economic growth (Grossman & Krueger, 1995).

In conclusion, this research provides a deep understanding of the factors affecting groundwater management within the framework of the Environmental Kuznets Curve. It focuses on the requirement of a blended approach in environment, economic, technological advancements, and economic growth and the consideration of all factors, which is essential for groundwater management. This study contributes to the broader goal of achieving sustainable groundwater management globally.

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