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Beyond Growth: Sectoral Water Use Efficiency as the Decisive Factor for Reversing Water Stress in the EU toward Sustainable Development Goals – A PSTR Approach

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Beyond Growth: Sectoral Water Use Efficiency as the Decisive Factor for Reversing Water Stress in the EU toward Sustainable Development Goals – A PSTR Approach

Celil AYDIN[1,*] , Onur BAYRAKCI[2]

Abstract

This study analyses the nonlinear relationship between economic growth and water stress in 25 EU countries over the period 2003–2022 using the Panel Smooth Transition Regression (PSTR) method. The findings indicate that the validity of the Environmental Kuznets Curve (EKC) hypothesis varies across sectors. At the aggregate economy level, on both sides of the $16,074 income threshold, growth increases water stress, albeit with diminishing intensity. In the sectoral analysis, beyond the threshold value of $14,780 in the agricultural sector, growth reduces water stress, thereby confirming the EKC hypothesis. In the industrial and services sectors, the hypothesis is not supported. However, the most significant finding is that when sectoral water-use efficiency is incorporated into the model as a threshold variable, the EKC hypothesis holds across all three sectors. Exceeding the calculated efficiency thresholds—$456.7/m³ for agriculture, $948.6/m³ for industry, and $2,162.5/m³ for services—leads to sectoral growth with a water-stress-reducing effect. These results reveal that economic growth alone does not alleviate water stress; rather, the determining factor is sectoral water use efficiency. Furthermore, with respect to achieving the Sustainable Development Goals (SDG)—particularly those related to clean water and sanitation, responsible production and consumption, and industry, innovation, and infrastructure—this study demonstrates that the growth rate alone is insufficient; the key determinant is sectoral water productivity. It is critically important for policymakers to move away from growth-oriented strategies, set sector-specific efficiency targets, and develop an integrated policy framework aligned with the EU Water Framework Directive and the objectives of the European Green Deal.

Keywords: Water stress, Environmental Kuznets Curve, sectoral water use efficiency, PSTR, Sustainable Development Goals

I. INTRODUCTION

Water, as a resource whose value is indisputable for humans and other living beings, as well as for ecosystems and habitats, for existence and survival, has attracted living beings throughout history. However, freshwater resources worldwide are very limited; only 2.5% of all water on Earth is usable as

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freshwater, and the majority of this water is contained in glaciers that are difficult to access (Oki & Kanae, 2006). While approximately 747,000 people worldwide lack access to safe drinking water, 198,178 people have died from diseases related to inadequate sanitation and contaminated water in the first three months of 2026 (Worldometer, 2026). Although developed countries have relatively developed water infrastructures, they face serious pressures on water resources due to increasing population, urbanisation, and the effects of climate change. Global freshwater resources are facing growing threats from anthropogenic use and the increasing impacts of climate change (Vörösmarty et al., 2010).

As an urgent and defining challenge of our era, climate change is now one of the greatest environmental threats. It disrupts the global hydrological cycle and directly affects the quantity, quality, and accessibility of freshwater resources (IPCC, 2023) Water is indispensable to ecosystems and human life. It is seen as a strategic natural capital with no alternative for sustainable development and as a 'global common good' (GCEW, 2023).

From the perspective of the European Union (EU), the strategic value of water has been elevated to the highest level by the European Green Deal; the protection and efficient use of water resources have been placed at the centre of the continent's transition process to a climate-neutral economy (European Commission, 2019). The fact that approximately four billion people worldwide are facing severe water scarcity (Mekonnen & Hoekstra, 2016) has turned the management of water from merely an environmental issue into a macroeconomic security and welfare problem that needs to be supported by legal regulations such as the Water Framework Directive (2000/60/EC) (European Parliament and Council of the European Union, 2000).

In EU countries, the protection and efficient management of water resources has become a legal obligation, especially within the scope of the Water Framework Directive (2000/60/EC), and this directive aims to achieve good status of water bodies in all member states (Díaz-Cano et al., 2025). Scarce freshwater resources have faced serious problems due to consumption and pollution pressures; it is evident that the risks and dangers posed by global warming to all environmental elements are also very high for freshwater resources (IPCC, 2023). Specifically for Europe, data from the European Environment Agency show that approximately 20% of the continent's territory and 30% of its population face this problem directly every year, and that Southern Europe, in particular, has become one of the main regions of insufficient water resources due to climate change (EEA, 2023a).

According to the European Environment Agency, groundwater provides about two-thirds of drinking water in the EU and helps wetlands and rivers. In 2021, 91% of the groundwater area was checked. Countries reported that 77% of the groundwater area was in good chemical condition. However, insufficient water affects even more people because poor water quality or shortages can harm both public

water supplies and healthy ecosystems. Nutrients and pesticides pose significant threats to groundwater: 14% of areas are in poor condition due to nutrients, and 10% due to pesticides (EEA, 2024). Studies show that population growth and economic development are the main drivers of the looming water crisis, as both increase water use, either by raising food demand or by making each person use more (Mekonnen & Hoekstra, 2016). Hoekstra and Wiedmann (2014) show that when people have more money, their habits change, such as choosing foods that require more water, which increases water use and worsens the water issue. More people mean more food and water are needed, and as the economy grows, people use even more water, putting more strain on current water sources (Kummu et al., 2016). This leads to water stress, driven by economic growth, poor development, pollution, and water waste (Li & Zhao, 2026). Here, water stress is linked to a place's level of development: as the economy and living standards rise, so does water stress. Breaking this cycle requires protecting water sources, using water efficiently, and ensuring growth plans are sustainable.

Water is seen to have a very important role in the implementation of the Sustainable Development Goals. The clean water goal, accepted as the 6th Sustainable Development Goal, emerges not only as part of the other 17 goals but also as a prerequisite for their realisation, and the reduction of water stress is at the centre of this goal (UN, 2015). Although 27 EU countries perform above the world average in achieving SDG 6 targets, they face significant challenges, especially in issues such as water pollution, pollution from nitrates and pesticides, and the degradation of water ecosystems; these factors reduce the availability of existing water resources and increase water stress (EEA, 2023b). The SDG Indicator 6.4.1 report published by FAO addresses changes in water use efficiency over time and focuses especially on the concept of economic decoupling from water use and its implementation in policy-making, emphasising the role of increased efficiency in reducing water stress (Rossi et al., 2019). According to the European Environment Agency, approximately 20% of EU member countries are under water stress, and this rate is expected to increase due to climate change (EEA, 2024). At this point, it emerges that not only is the increase in efficiency critical for reducing water stress, but also the re-evaluation of the development model is equally critical.

The relationship between development and water stress is bidirectional and complex. In the early stages of economic development, industrialisation, urbanisation, population growth, and the expansion of agricultural production rapidly increase water demand, placing pressure on existing freshwater resources. Building on this, Rock (1998) found that as countries develop, per capita income initially increases water use; however, beyond a certain income level, growth slows due to technological efficiency and structural transformation (Rock, 1998). In a related vein, Kummu et al. (2016) state that global water consumption increased fourfold during the 20th century, and the proportion of the world population experiencing clean water problems rose from 14% to 58% (Kummu et al., 2016). Taken together, these findings show that uncontrolled development can increase water stress.

On the other hand, increasing water stress is a primary constraint on development, leading to reduced agricultural productivity, disruptions in energy production, higher industrial costs, poorer public health, and deeper income inequalities. OECD findings stress that water scarcity exerts direct and indirect pressure on economic growth and reduces productivity in water-dependent sectors (Hertel & Liu, 2016). Similarly, a panel data study of 33 countries demonstrates that water stress undermines both environmental quality and sustainable development (Ahmad et al., 2026). Thus, a nonlinear, reciprocal relationship exists between development and water stress, with effective water management policies being essential for sustainable growth. This interaction must be evaluated not only in terms of water quantity and accessibility, but also of water quality and environmental degradation. Studies, especially from EU countries, highlight the impact of economic growth on water pollution, contributing meaningfully to the debate on water stress.

Studies examining the relationship between water pollution and economic growth, particularly in EU countries, generally support the EKC hypothesis and have important implications for water stress. For example, in their classic study of 42 countries, Grossman and Krueger (1995) found an inverted-U-shaped relationship between water pollution indicators and per capita income. This relationship suggests that, after a certain income level, water stress may decrease as water pollution declines (Grossman & Krueger, 1995). Similarly, Shafik and Bandyopadhyay (1992), in their comprehensive World Bank study, analysed water quality indicators and income levels, noting that water pollution increases at low-income levels and begins to decrease at middle-income levels (Shafik & Bandyopadhyay, 1992).

Frontuto et al. (2025) examined the link between GDP per capita and water demand using the CWASI database, which spans 121 countries over 24 years. Their study found a moderate inverted-U relationship between production water footprint and income, while consumption water footprint steadily increases. This indicates that water-efficiency improvements from economic growth, technology, or governance have not reversed global freshwater demand trends, and water stress remains (Frontuto et al., 2025).

Empirical studies focusing on Europe, particularly the Euro Area, indicate that economic growth generates nonlinear, threshold-dependent effects on water stress; however, beyond a certain income level, technological progress, regulatory frameworks, and improvements in water-use efficiency may alleviate pressure on water resources (Esen et al., 2020). Recent analyses examining the relationship between water footprint and economic growth reveal that advanced economies have the potential to decouple growth from water consumption through technological innovation, thus supporting the inverted-U-shaped relationship predicted by the EKC hypothesis (Esen et al., 2024; Kong et al., 2021; Paolo Miglietta et al., 2017) Jia et al. (2006), in their study examining the relationship between environmental efficiency and economic growth in developed countries, showed that technological development and structural transformation increase water use efficiency, lowering the turning point of the EKC and enabling water stress to begin decreasing at lower income levels (Jia et al., 2006). Esen et

al. (2020), in their panel threshold regression model study examining 9 European countries for the period 1995-2013, analysed the effect of per capita income on water stress; they found that growth below the threshold levels had no statistically significant effect on water stress, while the growth rate above the threshold increased the stress on water resources (Esen et al., 2020). Sesma- Martín and Puente-Ajovin (2022), using the ARDL model, tested the existence of the EKC for water withdrawal in the thermoelectric sector in Spain; they showed that there is a direct relationship between per capita income and water withdrawal and that water needs decrease after reaching an estimated turning point (Sesma-Martín & Puente-Ajovín, 2022).

These empirical findings show that the relationship between economic growth and water stress should be addressed not only in terms of quantitative resource use but also within the framework of broader environmental degradation dynamics. EKC hypothesis, which is one of the most important approaches theoretically explaining this interaction, takes its name from Nobel laureate economist Simon Kuznets and is based on the inverted-U shaped model that Kuznets developed to explain the relationship between income distribution and economic growth. Indeed, Simon Kuznets (1955) argued that income inequality increases in the early stages of economic development but tends to decrease after a certain level of development (Kuznets, 1955). In the subsequent literature, this approach was adapted to environmental indicators; it has been argued that environmental degradation increases in the early periods of economic growth due to industrialization, urbanization and intensive resource use, and after per capita income reaches a certain turning point, environmental quality begins to improve thanks to technological progress, increased institutional capacity and stricter environmental policies (Arbulú et al., 2025; Grossman & Krueger, 1991; T., 1993). When the empirical literature on the validity of the EKC hypothesis is examined, it is seen that the hypothesis is tested using different environmental indicators, and while CO_2 emission is generally preferred as an indicator of environmental degradation, alternative indicators such as water pollution and ecological footprint are also used (Thompson, 2012; Ulucak & Bilgili, 2018). While some of the studies present findings supporting the EKC hypothesis, they also show that the choice of environmental indicator plays a decisive role in the validity of the hypothesis (Dinda, 2004). It is understood that the differences between the findings largely stem from this preference, and water stress stands out as a critical environmental indicator that can be used in testing the EKC hypothesis. Furthermore, the use of water stress as an indicator of pressure on renewable water resources in testing the EKC hypothesis represents an approach that has so far remained limited in the literature but is gradually gaining importance. In this context, the dynamic interaction between the level of development and water stress is also evaluated within the framework of the EKC hypothesis; it is argued that in the early stages of economic growth, water demand and pollution increase, deepening water stress, but as the income level rises, this pressure can be reduced thanks to efficiency improvements, infrastructure investments and sustainable water management policies (Grossman & Krueger, 1991).

The EKC hypothesis has been tested in the literature mainly using aggregate economic growth indicators; however, it has been overlooked that the effects of economic activities on the environment, especially on water resources, differ significantly across sectors. Sectoral analyses reveal that the relationship between economic growth and environmental degradation varies significantly across sectors, as each sector differs in production processes, energy consumption, and technology use (Montagna et al., 2025). In this context, just as the contributions of economic sectors to the economy are heterogeneous, their environmental pressures also differ; therefore, examining the EKC hypothesis at the sectoral level is of great importance. When evaluated by water consumption, this difference becomes even more pronounced. The pressures of the agriculture, industry, and services sectors on water resources differ from one another both quantitatively and qualitatively, and analyses conducted at the aggregate economy level can mask these sector-specific dynamics (Esen et al., 2020). Therefore, the EKC hypothesis needs to be tested separately for the relationship between water stress and the sizes of the agriculture, industry and services sectors.

Within the EKC framework, the effect of economic growth on water stress is not direct but is largely mediated by water-use efficiency. In many regions, freshwater withdrawals first increase with growth, but then decrease or stabilise once societies reach a certain level of development and begin to invest in water efficiency and reuse (El Haddadi et al., 2025). This dynamic directly overlaps with the turning-point mechanism that underlies the EKC. The environmental improvements observed after the income threshold is exceeded are made possible by strengthening regulatory frameworks, technological progress, and the transition to more sustainable production and consumption patterns (Arbulú et al., 2025). However, whether this transformation occurs depends on water-use efficiency. An increase in water-use efficiency means a country decouples its economic growth from water consumption; in other words, the economy can continue to grow without needing more water (FAO & UN-Water, 2024). Therefore, water-use efficiency is the primary mechanism that determines whether economic growth increases or reduces water stress.

This study is thought to contribute to the literature in many respects. Firstly, it supports the EKC hypothesis by showing that the relationship between water stress and economic growth is nonlinear. Furthermore, it evaluates this relationship not only at the aggregate economy level but also separately in the agriculture, industry and services sectors. On the other hand, the role of water use efficiency in the relationship between water stress and economic growth is examined on a sectoral basis. Secondly, it is the use of the PSTR method developed by Gonzalez, Terasvirta and van Dijk (2005) in modelling the nonlinear relationship between water stress and economic growth. Many methods can be applied to model the nonlinear relationship. One of these methods is the quadratic model. There is an important limitation to using this method. Using the square of growth in the quadratic model in the water stress-economic growth relationship imposes a priori restrictions that the effect of economic growth on water

stress increases and decreases monotonically and symmetrically depending on the level of growth rate. Moreover, the negative intervals of the relationship may differ in their absolute effects from the positive intervals. Another method is the Panel Threshold Regression (PTR) model developed by Hansen (1999) (Hansen, 1999). However, the PTR approach assumes that parameters show abrupt transitions between regimes. The PSTR model is a differentiated version of the PTR model because it allows regression coefficients to change smoothly as one regime or state transitions to another. In addition, the PSTR approach can test whether there is one or more levels of the threshold, and, unlike many other models in the existing literature that only allow exogenous determination, it can determine threshold values endogenously. The endogenous determination of threshold levels enables the researcher to identify precise levels, providing a significant advantage in analysing the real relationship between water stress and economic growth. Finally, this study examines EU countries within a holistic, up-to-date framework and establishes a direct connection between their current policies, such as the Green Deal, Zero Pollution Action Plan, and Water Framework Directive. In this way, it shows that water stress is not only a technical problem but also a strategic governance area requiring policy integration. In other words, the study re-questions the water stress-economic growth relationship for 25 EU countries for the period 2003-2022, and this time interval covers the transition in the EU's water management between the 'good status target' (WFD) and the 'climate-neutral economy' (Green Deal).

This study investigates the effect of economic growth on water stress using the PSTR method, an innovative nonlinear model developed by Gonzalez, Terasvirta and van Dijk (2005), at both the aggregate economy level and for the agriculture, industry, and services sectors. The study examines the validity of the EKC hypothesis across 25 EU countries over the period 2003-2022. Furthermore, it examines the role of sectoral water use efficiency in the water stress-economic growth relationship within the context of the EKC separately for each sector. The remainder of this study is organised as follows: Section 2 models the relationship between water stress and economic growth within the EKC framework. Section 3 explains the adopted methodology. Section 4 presents the data sources and empirical results, and Section 5 concludes with policy implications.

II. MODEL

In this study, a model was established based on the studies of Katz (2015), Esen et al. (2020), Esen et al. (2024) and Arbulú et al. (2025) to test the EKC hypothesis in the relationship between water stress and economic growth for EU countries, and is shown in Equation (1).

$$LnWS_{i,t} = \beta_0 + \beta_1 LnGDP_{i,t} + \varepsilon_{i,t} \quad (1)$$

In Equation (1), *LnWS* denotes water stress in logarithmic form, *LnGDP* denotes Gross Domestic Product in logarithmic form, ε denotes the error term, *t = 1, 2, …, T* denotes the time period, and *i = 1, 2, 3…, N* denotes the countries.

Although the EKC hypothesis has been tested in the literature mainly with aggregate economic growth indicators, it has been overlooked that pressure on water resources differs across sectors (Montagna et al., 2025). Therefore, in this study, it is aimed to test sectoral dynamics within the framework of the EKC by testing the relationship between water stress and the sizes of the agriculture, industry and services sectors separately. In order to test the validity of the EKC hypothesis on a sectoral basis, the model in Equation (1) has been revised for the agriculture, industry and services sectors, and the established models are shown in Equations (2), (3) and (4), respectively.

$$LnWS_{i,t} = \beta_0 + \beta_1 LnAgritoGDP_{i,t} + \varepsilon_{i,t} \quad (2)$$

$$LnWS_{i,t} = \beta_0 + \beta_1 IndtoLnGDP_{i,t} + \varepsilon_{i,t} \quad (3)$$

$$LnWS_{i,t} = \beta_0 + \beta_1 LnServtoGDP_{i,t} + \varepsilon_{i,t} \quad (4)$$

In Equations (2), (3) and (4), *LnWS* denotes water stress in logarithmic form; *LnAgritoGDP*, *LnIndtoGDP* and *LnServtoGDP* denote, respectively, the share of the agriculture, industry and services sectors in total GDP in logarithmic form.

Within the EKC framework, the effect of economic growth on water stress is not direct but is largely mediated by water-use efficiency. Therefore, water use efficiency is the main mechanism that determines whether economic growth increases or reduces water stress; for this reason, it should be included in the models as a threshold variable.

Water-use efficiency levels can vary significantly across sectors. Measuring water use efficiency for the agriculture, industry and services sectors as the ratio of sectoral value added to the volume of water used reveals the obstacles to decoupling economic growth from water consumption and the sector-specific conditions of this decoupling (Hellegers & van Halsema, 2021). Therefore, it is thought that including water-use efficiency at the sectoral level in the model will more accurately reveal the validity of the EKC hypothesis in the context of water stress. In order to test the validity of the EKC hypothesis, the models in Equations (2), (3) and (4) have been revised for the agriculture, industry and services sectors, and the established models are shown in Equations (5), (6) and (7), respectively.

$$LnAgritoWS_{i,t} = \beta_0 + \beta_1 LnAgritoGDP_{i,t} + \varepsilon_{i,t} \quad (5)$$

$$LnIndtoWS_{i,t} = \beta_0 + \beta_1 IndtoLnGDP_{i,t} + \varepsilon_{i,t} \quad (6)$$

$$LnServtoWS_{i,t} = \beta_0 + \beta_1 LnServtoGDP_{i,t} + \varepsilon_{i,t} \quad (7)$$

In Equations (5), (6) and (7), *LnAgritoWS*, *LnIndtoWS* and *LnServtoWS* denote, respectively, the contributions of the agriculture, industry and services sectors to total water stress in logarithmic form; *LnAgritoGDP*, *LnIndtoGDP* and *LnServtoGDP* denote, respectively, the share of the agriculture, industry and services sectors in total GDP in logarithmic form**.**

III. Methodology

In this study, we aim to clarify the purpose of employing the Panel Smooth Transition Regression (PSTR) model: to analyse how the nonlinear effect of water stress on economic growth across 25 EU countries may vary with levels of water-use efficiency. The PSTR model, developed by Gonzalez, Terasvirta, and van Dijk (2005), is chosen for its capacity to capture these regime-dependent shifts (González et al., 2005). Therefore, a two-regime fixed PSTR model has been constructed, as outlined in equation (1) and presented in equation (8), specifically to assess these varying effects.

$$LnWS_{i,t} = \mu_i + \beta_0 LnGDP_{i,t} + \beta_1 LnGDP_{i,t} * g(q_{i,t}; \gamma, \theta) + \varepsilon_{i,t} \quad (8)$$

In Equation (8), *LnWS* and *LnGDP* denote water stress and GDP, respectively, in logarithmic form; ε denotes the error term; *t = 1, 2, …, T* denotes time; and *i = 1, 2, 3…, N* denotes regions. μ_i denotes region-specific fixed effects, and q_i denotes the threshold variable (*GDPper*). In Equation (8), $g(q_{i,t}; \gamma, \theta)$ is used as the transition function and is expressed in logistic function form as in Equation (9):

$$g(q_{i,t}; \gamma, \theta) = [1 + \exp(-\gamma(q_{i,t} - \theta))]^{-1} \quad (9)$$

In Equation (9), the θ parameter is the threshold that distinguishes the two regimes, where $g(q_{i,t}; \gamma, \theta) = 0$ for one regime and $g(q_{i,t}; \gamma, \theta) = 1$ for the other. The parameter γ, called the smoothing parameter, controls how gradually the transition function changes value, and thus how the model moves between regimes. If γ approaches infinity ($\gamma \rightarrow \infty$), the transition from 0 to 1 in the transition function becomes abrupt when the threshold variable equals θ. This is similar to the PTR model, which bases its estimation on the PTR approach. If γ approaches zero ($\gamma \rightarrow 0$), the transition function becomes constant. When γ equals zero ($\gamma = 0$), the model simplifies to a linear form. In that case, estimation uses the panel within estimator (Fouquau et al., 2008).

The transition function is continuous in the transition variable and takes values between 0 and 1. In Equation (8), if the transition function is 0 ($g(q_{i,t}; \gamma, \theta) = 0$), the regression coefficient is β_0; if it is 1($g(q_{i,t}; \gamma, \theta) = 1$) , the regression coefficient is $\beta_0 + \beta_1$. If the transition function is between 0 and 1

$(0 < g(q_{i,t};\gamma,\theta) < 1)$, the regression coefficient becomes the weighted average of β_0 and β_1. In the PSTR model, it is better to interpret coefficient signs than their direct values (Fouquau et al., 2008). This approach clarifies if the independent variable's effect on the dependent variable is positive or negative, and interprets time-varying elasticities (Guloglu & Nazlioglu, 2013).

For the purpose of examining the nonlinear relationship between water stress and economic growth on a sectoral basis, two-regime fixed PSTR models have been established based on the models in equations (2), (3) and (4), and are shown in equations (10), (11) and (12):

$$LnWS_{i,t} = \mu_i + \beta_0 LnAgritoGDP_{i,t} + \beta_1 LnAgritoGDP_{i,t} * g(q_{i,t};\gamma,\theta) + \varepsilon_{i,t} \quad (10)$$

$$LnWS_{i,t} = \mu_i + \beta_0 LnIndtoGDP_{i,t} + \beta_1 LnIndtoGDP_{i,t} * g(q_{i,t};\gamma,\theta) + \varepsilon_{i,t} \quad (11)$$

$$LnWS_{i,t} = \mu_i + \beta_0 LnServtoGDP_{i,t} + \beta_1 LnServtoGDP_{i,t} * g(q_{i,t};\gamma,\theta) + \varepsilon_{i,t} \quad (12)$$

For the purpose of examining water use efficiency in the nonlinear relationship between water stress and economic growth on a sectoral basis, two-regime fixed PSTR models have been established based on the models in equations (5), (6) and (7), and are shown in equations (13), (14) and (15):

$$LnAgritoWS_{i,t} = \mu_i + \beta_0 LnAgritoGDP_{i,t} + \beta_1 LnAgritoGDP_{i,t} * g(q_{i,t};\gamma,\theta) + \varepsilon_{i,t} \quad (13)$$

$$LnIndtoWS_{i,t} = \mu_i + \beta_0 LnIndtoGDP_{i,t} + \beta_1 LnIndtoGDP_{i,t} * g(q_{i,t};\gamma,\theta) + \varepsilon_{i,t} \quad (14)$$

$$LnServtoWS_{i,t} = \mu_i + \beta_0 LnServtoGDP_{i,t} + \beta_1 LnServtoGDP_{i,t} * g(q_{i,t};\gamma,\theta) + \varepsilon_{i,t} \quad (15)$$

In the models in equations (10), (11) and (12), GDP per capita (*GDPper*) is used as the threshold variable, while in the models in equations (13), (14) and (15), Irrigated Agriculture Water Use Efficiency (*AgriWUE*), Industrial Water Use Efficiency (*IndWUE*) and Services Water Use Efficiency (*ServWUE*) are used as the threshold variable, respectively.

IV. Data Set and Empirical Results

A. Data Set

In this study, the nonlinear relationship between water stress and economic growth, and the role of sectoral water-use efficiency in this relationship, are examined in the context of the EKC hypothesis using seven separate models. In the first four models, water stress is the dependent variable; in the last three models, the contributions of the agriculture, industry, and services sectors to total water stress are the dependent variables, respectively. Furthermore, while GDP per capita is used as the threshold variable in the first four models, the shares of the agriculture, industry and services sectors in total GDP are used as the threshold variable in the last three models, respectively. In the study, the data were analysed for 25 EU countries for the period 2003-2022. Additionally, Croatia and Slovenia were excluded from the EU country group due to missing data. The data used in the analysis were obtained

from the AQUASTAT database (AQUASTAT, 2026). Explanatory information regarding the variables is shown in Table 1, while descriptive statistics are presented in Table 2.

[Table 1 here]

As shown in Table 2, Malta has the highest water-stress value at approximately 91.29% in 2013, while Latvia has the lowest at approximately 0.99% in 2014. On the other hand, the average water stress value is 77.854 for Malta and 1.317 for Latvia. When looking at the data for water stress on a sectoral basis, the country with the highest contribution of the agriculture and services sectors to total water stress is Malta, with approximately 58.44% and 51.06%, respectively, while the country with the highest contribution of the industry sector to total water stress is Belgium, with 71.79%. In terms of water use efficiency, the country with the highest value is the Netherlands, with approximately 53.69 US$/m³ in the agriculture sector; Luxembourg, with 5,248.84 US$/m³ in the industry sector; and Austria, with 8,044.52 US$/m³ in the services sector. The country with the highest per capita income is Luxembourg, at 133,867.20$, while the country with the lowest per capita income is Bulgaria, at 2,670.58$.

[Table 2 here]

B. Empirical Results

In this study, which examines the nonlinear relationship between water stress and economic growth and the role of sectoral water-use efficiency in this relationship in the context of the EKC hypothesis, using seven separate models, cross-sectional dependence tests were first performed for both the series and each model. In panel data analyses, the assumption of independence across countries is critical; however, countries are often economically interdependent. Because unaccounted-for cross-sectional dependence can compromise result reliability, the study employed multiple tests $CDLM_1$ (Breusch & Pagan, 1980), $CDLM_2$ (Pesaran, 2004), and Bias-Corrected LM (Pesaran et al., 2008) to robustly identify cross-sectional dependence. The rationale for selecting these tests lies in their complementary ability to capture different forms and degrees of cross-sectional dependence. The results for the series are presented in Table 3a.

[Table 3a here]

According to the results in Table 3a, there is cross-sectional dependence among the series. In the next step, the Breusch-Pagan (1980) test, the Pesaran (2004) test, and the Pesaran, Ullah, and Yamagata (2008) test were applied to detect cross-sectional dependence in each model, and the results are shown in Table 3b.

[Table 3b here]

According to Table 3b, cross-sectional dependence is present in each model. While models typically assume homogeneous slopes, the effect of the explanatory variable can differ across countries. Thus, estimators assuming homogeneity can produce biased results (Guven et al., 2019). Given cross-sectional dependence and possible coefficient heterogeneity, the next step was to apply the Delta test (Hashem Pesaran & Yamagata, 2008) to assess slope homogeneity; results appear in Table 4.

[Table 4 here]

According to the results in Table 4, the null hypothesis of slope homogeneity is rejected in the models, indicating that the coefficients are heterogeneous and that the effects differ across countries. The presence of cross-sectional dependence in the series and the models, along with coefficient heterogeneity, necessitates the application of second-generation unit root tests. In this context, the Fourier Panel Stationarity Test, which accounts for nonlinearities and structural breaks, was applied. The Fourier Panel KPSS test developed by Nazlıoğlu and Karul (2017) offers advantages over other unit root tests, as it accounts for heterogeneity, structural breaks, and cross-sectional dependence (Nazlioglu & Karul, 2017; Tiwari et al., 2021). The Fourier Panel Stationarity Test results are shown in Table 5.

[Table 5 here]

According to the results in Table 5, the null hypothesis that all series are stationary is rejected, and the series are found not to be stationary at the 5% level. This situation necessitates detecting the long-term relationship in the models using cointegration methods. Therefore, the long-term relationship in the models used in the study is tested with the Fractional frequency flexible Fourier form for the panel cointegration test (FFFFF). The test offers a panel cointegration method that is robust to nonlinearity, unknown number and forms of structural breaks, and cross-sectional dependence. In the method, the bootstrap panel cointegration test is used to resample the cross-sectional correlation. Here, a unit root is implicitly imposed by summing the residuals. The cointegration test results performed for each model are shown in Table 6.

[Table 6 here]

The cointegration test results in Table 6 indicate that each model is statistically significant and that there is a long-term cointegration relationship. Following this determination, the next step is to test the linear model against the nonlinear model. The results of the Wald Test (*LM*), Fisher Test (LM_F) and LRT Test (*LRT*) calculated for testing linearity and determining the number of transition functions for each model are shown in Table 7a.

[Table 7a here]

As shown in Table 7a, the *LM*, LM_F, and *LRT* tests reject the null hypothesis of linearity at the 1% significance level for all models. Therefore, the alternative hypothesis of at least one nonlinear threshold effect is accepted, indicating that a linear model is not suitable for this model. After rejecting linearity, the next step is to determine the number of regimes. To do this, the *LM*, LM_F, and *LRT* tests were repeated for each model, with the results presented in Table 7b.

[Table 7b here]

Table 7b shows that none of the models rejects the hypothesis of a single threshold effect. Therefore, each model is assumed to have a single threshold effect and is estimated using a two-regime approach. Next, Model I in equation (1) tests if there is a nonlinear link between water stress and economic growth for 25 EU countries, while Models II, III, and IV in equations (2), (3), and (4) do the same for agriculture, industry, and services. All models use the two-regime approach, and the results are in Table 8a.

[Table 8a here]

As indicated in Table 8, the smoothing parameter is quite small in each model (1.111, 9.790, 8.599, and 14.746 for Models I, II, III, and IV, respectively). A small smoothing parameter indicates that the transition from the first to the second regime in each model is smooth. This situation is shown in Figure 1.

[Figure 1 here]

As shown in Table 8a, Model I tests the EKC hypothesis in the nonlinear relationship between water stress and economic growth, with a GDP per capita threshold of \$16,074.67 ($e^{9.685}$=16,074.67). Below this threshold, the GDP coefficient is statistically significant and positive (1.203); above the threshold, it remains significant and positive (0.966) but is lower. Thus, economic growth increases water stress in both regimes, though the impact diminishes as development progresses. In the early development stage, expanding water-intensive sectors like agriculture and industry drive up production and water demand. Increasing populations and industries further strain water resources and contribute to wastewater, explaining the negative link between growth and water stress (Almeida et al., 2024). As incomes rise, economies shift toward services and high-tech sectors, thereby reducing relative water demand. However, while not adopting advanced clean technologies and supporting environmental legislation eases demand, these measures are insufficient to reverse the growth-water stress relationship (Wang et al., 2024).

In Models II, III and IV, which allow testing the EKC hypothesis separately in the agriculture, industry and services sectors in the nonlinear relationship between water stress and economic growth in EU

421 countries, respectively, the threshold values for GDP per capita are found to be 14,779.55$, 13,807.95$
422 and 13,725.35$ ($e^{9.601}$=14,779.55, $e^{9.533}$=13,807.95 and $e^{9.527}$=13,725.35, respectively). In the first
423 regime, where GDP per capita is below the threshold value in the agriculture, industry, and services
424 sectors, the coefficient for the GDP share of the relevant sector is positive and statistically significant in
425 all sectors (0.319, 0.350, and 0.508 for the agriculture, industry, and services sectors, respectively). In
426 the second regime, above the threshold value, this coefficient is statistically significant and positive in
427 the industry and services sectors (0.186 and 0.395, respectively), although it is lower than in the first
428 regime; it is also statistically significant and negative (-0.121) in the agriculture sector. These findings
429 show that the effect of economic growth on water stress in the industry and services sectors is positive
430 in both regimes, but it weakens as development increases. In contrast, in the agriculture sector, the
431 direction of the relationship changes once the threshold value is exceeded. This indicates that, on a
432 sectoral basis, the EKC hypothesis holds for the agriculture sector but not for industry and services. The
433 validity of the EKC hypothesis in the agriculture sector can be explained by strong institutional
434 interventions and implemented policies. Eco-schemes implemented under the common agricultural
435 policy, investments increasing irrigation efficiency, and regulations within the framework of the Water
436 Framework Directive reduce agricultural water demand (ECA, 2021). This finding is also consistent
437 with previous studies demonstrating the validity of the EKC hypothesis in the agricultural sector
438 (Zafeiriou et al., 2017). The reasons the EKC hypothesis does not hold in the industry and services
439 sectors are structural. In the industry sector, the fact that increases in energy and resource efficiency are
440 compensated by production increases due to the rebound effect, technological lock-in problems, and the
441 fact that a comprehensive transformation strategy for the EU's energy-intensive industries has not yet
442 been established, limits the decrease in water demand (Lemoine, 2020). In service sub-sectors such as
443 tourism, with increasing income, the simultaneous increase in water demand from tourism and
444 consumption, along with the adoption of water-saving technologies and increased environmental
445 awareness, does not reduce total water demand in the services sector but rather increases it or causes it
446 to remain at high levels (Arbulú et al., 2025).

447 In the context of the EKC, ensuring sustainability across all sectors depends on resource efficiency.
448 Water is a critical input with no alternative in most production processes. Therefore, its efficient use at
449 every stage, from source to end-user, is essential for protecting the environment and achieving economic
450 efficiency (Kanmaz et al., 2022). Models V, VI, and VII shown in equations (5), (6), and (7) examine
451 the role of sectoral water use efficiency in the nonlinear relationship between water stress and economic
452 growth for agriculture, industry, and services. These models are estimated with the two-regime model,
453 and the results appear in Table 8b.

454 **[Table 8b here]**

As indicated in Table 8b, the smoothing parameter is quite small in each model (0.527, 0.506, and 0.765 for Models V, VI, and VII, respectively). A small smoothing parameter indicates that the transition from the first to the second regime in each model is smooth. This situation is shown in Figure 2.

[Figure 2 here]

As seen in Table 8b, in Models V, VI and VII, which test sectoral water use efficiency in the context of the EKC hypothesis for the agriculture, industry and services sectors, respectively, in the nonlinear relationship between water stress and economic growth on a sectoral basis, the threshold values for water use efficiency in the agriculture, industry and services sectors are found to be 456.687 US$/m³, 948.612 US$/m³ and 2,162.456 US$/m³ ($e^{6.124}$=456.687, $e^{6.855}$=948.612 and $e^{7.679}$=2,162.456), respectively. In Models V, VI and VII, in the first regime where water use efficiency for the agriculture, industry and services sectors is below the threshold value, the coefficient for the GDP share of the relevant sector is positive and statistically significant in all sectors (0.468, 1.954 and 0.903 for the agriculture, industry and services sectors, respectively). In the second regime, above the threshold value, this coefficient becomes statistically significant and negative (-16.890, -1.163 and -0.308, respectively). These findings show that when water use efficiency is low, sectoral growth increases water stress, and as efficiency rises, this effect reverses. Therefore, the EKC hypothesis holds across all three sectors, and water-use efficiency constitutes a critical threshold mechanism. Considering the threshold values, while water use efficiency in the agriculture (456.687 US$/m³), industry (948.612 US$/m³) and services (2,162.456 US$/m³) sectors is below the threshold level, sectoral growth increases water stress; when the threshold is exceeded, a reducing effect emerges. When the regime coefficients are considered by magnitude, it is seen that in the first regime, where water use efficiency is below the threshold in all three sectors, the effect of sectoral growth on water stress originating in the relevant sector is weaker than in the regime above it. When comparing on a sectoral basis, the increase in the agriculture sector's share of GDP has a greater effect on sector-originated water stress than the other sectors.

The obtained findings largely overlap with the literature addressing the threshold mechanism in the water stress-economic growth relationship. Katz (2015) reveals that irrigated agriculture is the main driver of water stress in developing economies, whereas in developed economies, water efficiency and technological innovation enable a partial decoupling between growth and water consumption (Katz, 2015). This finding, when evaluated together with the fact that the threshold value calculated for the agriculture sector in this study remains significantly lower compared to other sectors and the strong positive effect of the increase in the share of agriculture in GDP on water stress, strongly supports the thesis that agricultural growth increases water pressure at a much higher level compared to other sectors under conditions where it remains below the threshold value. The fact that the threshold value calculated for the industry sector is approximately twice as high as that of the agriculture sector is consistent with the structural transformation theory used by Katz (2015): as the economy transforms from an intensive

agricultural structure to industry and from there to the relatively less water-intensive services sector, water use initially increases and then tends to decline only after a certain maturity threshold is exceeded. The fact that the services sector has the highest threshold value aligns with He's (2022) findings, which show that the service sector has lower water use and higher water efficiency than agriculture and industry (He et al., 2022).

When evaluated from the perspective of EU policies, the European Court of Auditors' report finds that agricultural supports under the CAP have not been consistently harmonised with water policy objectives, and water abstraction exemptions for farmers remain in countries facing intense water stress, such as Spain, Italy, and Portugal. EEA data shows that although total EU water abstraction decreased by 14% from 2000 to 2023, this decline stalled after 2010, with abstraction in agriculture, industry, and services rising again (EEA, 2025). Our study highlights that growth increases water stress in sectors not yet over the identified threshold. This finding underlines the urgency for EU-wide action and suggests that adopting the identified agricultural threshold as a CAP policy target could significantly strengthen efforts to reduce water stress.

V. Conclusion

The findings of this study, which examine the nonlinear relationship between water stress and economic growth for 25 EU countries over the period 2003–2022 within the framework of the PSTR model, reveal that the validity of the EKC hypothesis varies significantly across environmental and economic indicators and sectoral structures. In the analysis conducted at the aggregate economic growth level, it was found that on both sides of the income threshold of $16,074.67, economic growth increases water stress, with the rate of increase slowing only slightly after the threshold. This finding indicates that the EKC hypothesis cannot be validated at the aggregate economy level in the context of water stress and suggests that the insufficient adoption of advanced clean technologies, coupled with increasing drought, climate change, and demand pressures, has not yet reversed the relationship between economic growth and water stress (Almeida et al., 2024; Wang et al., 2024). When transitioning to sectoral analyses, the picture changes markedly. In the agriculture sector, once the income threshold (14,779.55$) is exceeded, agricultural growth begins to reduce water stress—thus the EKC hypothesis is confirmed. This result can be explained by the strong institutional intervention provided by the EU's Common Agricultural Policy (CAP) through eco-schemes, irrigation efficiency investments, and Water Framework Directive payments (ECA, 2021). Furthermore, this outcome aligns with studies showing that modern irrigation technologies, digital agriculture practices, and agricultural supports conditional on environmental criteria can reduce resource pressure (Pérez Zabaleta & Borrat Sanjuan, 2024; Zafeiriou et al., 2017) In contrast, in the industry sector, the hypothesis loses validity due to the rebound effect and technological

lock-in problems (Lemoine, 2020) In the services sector, income growth both encourages water-saving and drives water-intensive luxury consumption, weakening the hypothesis (Arbulú et al., 2025).

The most important contribution of the study is that, by including sectoral water-use efficiency as a threshold variable in the model, the EKC hypothesis holds across all three sectors. The most striking finding obtained is that, provided that water use efficiency exceeds a certain threshold level (456.687 for agriculture, 948.612 for industry and 2,162.456 $/m³ for services), the EKC hypothesis becomes valid in all three sectors, and it is confirmed that sectoral water use efficiency functions as a decisive mediating mechanism in the relationship between economic growth and water stress. This result is directly consistent with the findings of UN-Water (2024) (FAO & UN-Water, 2024), which emphasise that water-use efficiency is a fundamental tool for sustainable development.

When the study's findings are evaluated broadly, they show that economic growth alone does not reduce water stress; rather, sectoral transformation and water-use efficiency are the determining factors. Within this framework, it is of critical importance for policymakers to move away from growth-oriented strategies alone, to set sector-specific water use efficiency targets, to strengthen the economic pillar of the Water Framework Directive in the industry sector, and to develop an integrated policy framework aimed at implementing sector-specific tools such as ecological design standards in the services sector, for the EU to achieve its sustainable water management goals.

To implement this integrated framework, concrete, applicable policy steps need to be defined at the sectoral level. In the agriculture sector, drip irrigation and smart irrigation systems should be widespread, drought-resistant crops should be encouraged instead of water-intensive products, and agricultural supports should be tied to water efficiency instead of production quantity (FAO, 2021). In the industry sector, mandatory water-efficiency audits should be introduced for large enterprises, the reuse of treated wastewater should be encouraged, and a 'Water Impact Assessment' requirement should be introduced for new investments. In the services and tourism sector, water footprint standards should be applied to hotels and tourism facilities, greywater and rainwater reuse systems should be made mandatory, and a portion of tourism revenues should be allocated to local water infrastructure (Arbulú et al., 2025). Within the scope of urban policies, loss-leakage rates in municipal networks should be reduced, excessive consumption should be discouraged through progressive tariff systems, and rainwater harvesting systems should be supported in new buildings (Kingdom et al., 2006). Within the framework of macroeconomic policies, water efficiency indicators should be monitored alongside GDP, incentives for water-intensive investments in arid regions should be reviewed, and a basin-based water budget should be incorporated into development plans (OECD, 2023). For the European Union, sectoral water-efficiency targets should be set under the European Green Deal, the European Commission should condition agricultural support on water savings, and a common drought-resilience fund should be established for Southern European countries.

In conclusion, policymakers must move away from growth-oriented strategies. They should set sector-specific efficiency targets. It is essential to develop an integrated policy framework. This framework should align with the EU Water Framework Directive and the European Green Deal. This approach directly targets the efficient use of water resources. It also helps reduce water stress under Sustainable Development Goal 6 (Clean Water and Sanitation) and Goal 12 (Responsible Production and Consumption). Furthermore, promoting resource efficiency under Goal 9 (Industry, Innovation and Infrastructure) integrates economic growth with environmental sustainability. According to the findings, SDGs can be achieved not only through higher income levels. They also require exceeding threshold values of sectoral water use efficiency: 456.7 $/m³ for agriculture, 948.6 $/m³ for industry, and 2,162.5 $/m³ for services.

CRediT authorship contribution statement

Celil Aydin: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization, Data curation. **Onur Bayrakci:** Writing – original draft, Validation, Investigation, Formal analysis, Conceptualization.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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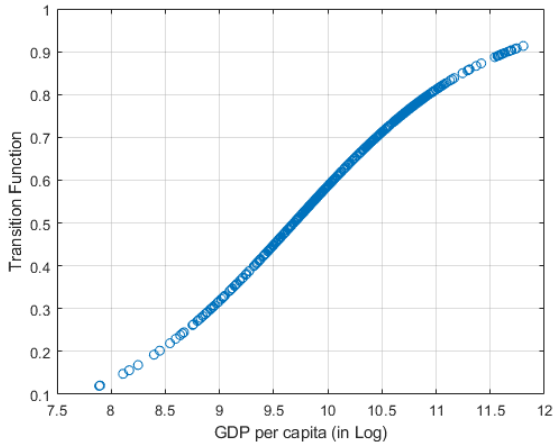
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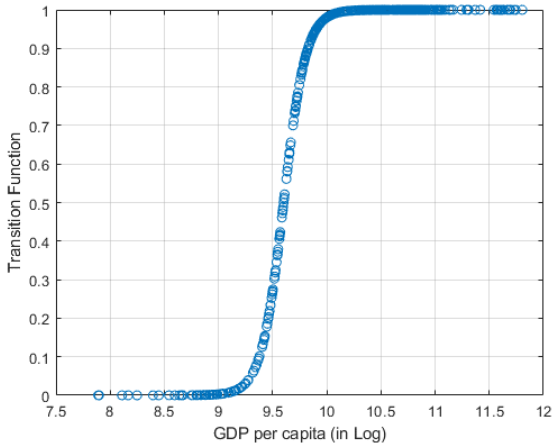
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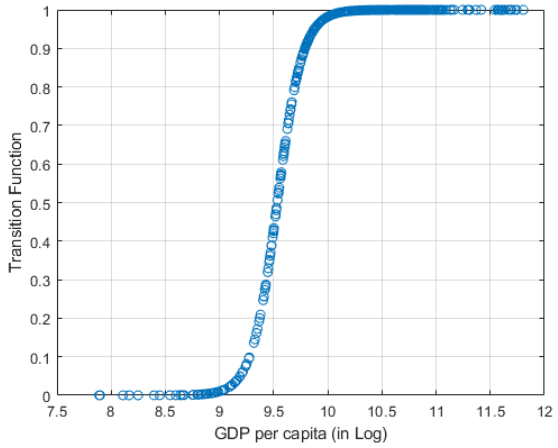
Model I



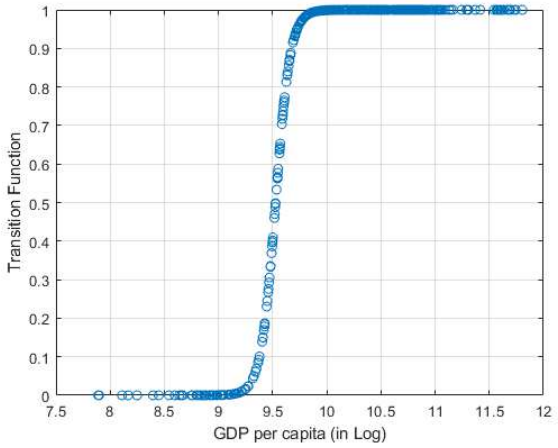
Model II



Model III



Model IV



752 **Figure 1.** Estimated transition function of the PSTR model against GDP per capita for main models

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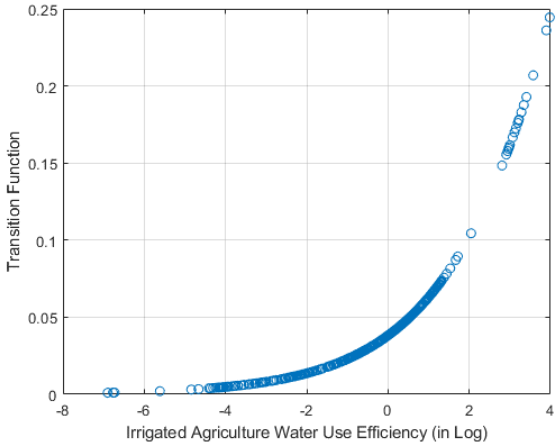
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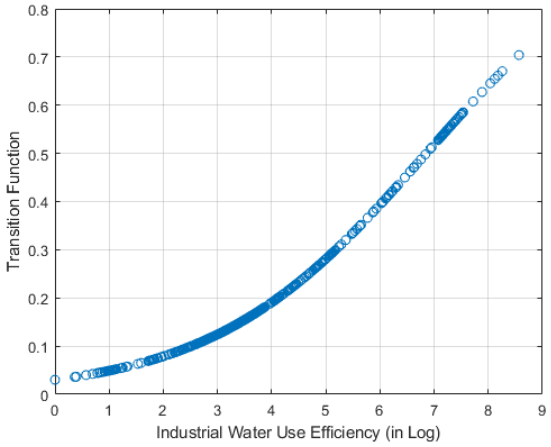
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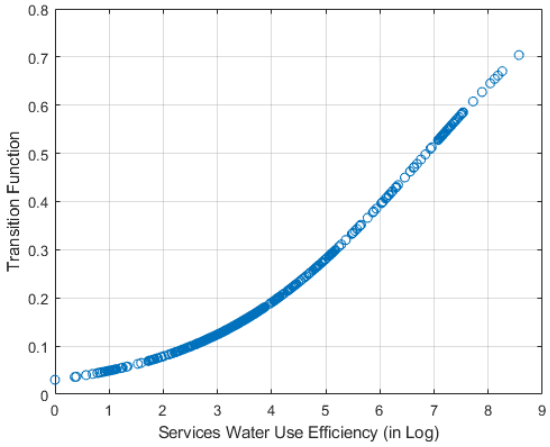
Model V



Model VI



Model VII



760 **Figure 2.** Estimated transition function of the PSTR model against Agriculture/ Industrial/ Services
761 Water Use Efficiency for sub-models

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Supplementary Files

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- Tables.docx