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Posted Date: 13 August 2025

doi: 10.20944/preprints202508.1002.v1

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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 August 2025 doi:10.20944/preprints202508.1002.v1

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Quantifying the Influence of Circular Economy and Climate Resilience on Freshwater Withdrawals Across Europe

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Abstract

Freshwater resources are increasingly pressured by socioeconomic development, climate variability, and evolving sustainability practices. This study investigates the combined influence of economic growth, circular economy adoption, climate resilience, and population size on freshwater withdrawals across European countries. Using multiple linear regression analysis, we quantify how these factors jointly impact national freshwater consumption. Data from Eurostat and the ND-GAIN Country Index were analyzed to assess circular material use rates, climate adaptation capacity, GDP per capita, and population effects on freshwater withdrawals. Results indicate that population size is the strongest and only statistically significant predictor of freshwater withdrawals, with larger populations correlating with increased water use. Although circular economy indicators and climate resilience show expected directions of influence, positive and negative respectively, their effects were not statistically significant in this model. Economic growth measured by GDP per capita also did not significantly affect freshwater withdrawals. These findings highlight that demographic factors remain dominant drivers of water demand in Europe, while the mitigating roles of circular economy practices and climate resilience require further investigation. The study underscores the importance of integrating population dynamics into water management policies and calls for enhanced empirical research to clarify the potential of sustainability strategies in reducing freshwater pressures.

Keywords: circular economy; freshwater withdrawals; economic factors; water resource management

JEL: Q25; Q57

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1. Introduction

Freshwater is an essential resource for human health, economic development, agriculture, and ecosystem sustainability. In Europe, freshwater availability is increasingly challenged by factors such as population growth, economic expansion, climate variability, and emerging sustainability paradigms. These pressures demand a thorough understanding of the key drivers behind freshwater withdrawals to inform effective resource management and policy decisions aimed at ensuring sustainable water use.

Despite extensive research on the socioeconomic determinants of water consumption [1,2] most studies have focused primarily on variables such as GDP and population, often neglecting the influence of emerging sustainability paradigms. Recent work has highlighted the potential of circular economy strategies to reduce resource use [3,4], yet few empirical analyses quantitatively assess how circular material use rates affect water consumption at the national level, particularly in Europe [5].

Similarly, climate resilience and adaptation have been identified as critical factors influencing water resource management [6],but their combined effects alongside economic indicators remain underexplored in cross-country regression frameworks [7]. This lack of integrated, data-driven research limits the ability of policymakers to develop holistic water management policies aligned with climate and circular economy objectives. Addressing this gap, the present study applies multiple linear regression analysis on 2021 European country data to examine the joint impact of circular economy practices, climate resilience, and traditional economic factors on water consumption.

Given these gaps and conflicting perspectives, this study aims to analyze the joint impact of economic development, circular economy practices, climate resilience, and population on freshwater withdrawals in European countries. Specifically, we test the following hypotheses:

H1: GDP per capita has a significant positive effect on freshwater withdrawals.

H2: Circular economy practices have a significant positive effect on freshwater withdrawals.

H3: Climate resilience has a significant negative effect on freshwater withdrawals.

H4: Population size has a significant positive effect on freshwater withdrawals.

The results are expected to inform sustainable water management policies that align economic growth with environmental and climate goals.

2. Background

2.1. Theoretical Foundations

2.1.1. Environmental Kuznets Curve (EKC) Theory and Water Use

In European countries, the link between economic development and freshwater withdrawals is complex and shaped by multiple factors, according to Usenata (2018). As economies grow, water demand rises across sectors, especially agriculture and industry, leading to potential over-extraction and pollution. This process often follows the Environmental Kuznets Curve (EKC), where water degradation initially worsens with income but improves once a certain threshold is reached, driven by improved regulations, infrastructure, and innovation. Effective water governance and investment in circular economy practices, such as wastewater recycling and efficient usage, are crucial in managing withdrawals sustainably. Moreover, technological advances and a shift toward service-oriented economies reduce water intensity. However, results vary across nations, highlighting the importance of robust policies and institutions in aligning economic growth with climate resilience and sustainable water management(Usenata, 2018).

The study by Masoud Hosseinzadeh, Sayed H. Saghaian, Zahra Nematollahi, and Naser Shahnoushi Foroushani (2022) confirms the presence of the Environmental Kuznets Curve (EKC) in the context of water use in Iran. Specifically, it finds that there is an inverted 'U'-shaped relationship between water consumption and economic growth in the agricultural and service sectors. This implies that as income increases, water use initially rises but then decreases after surpassing a certain income threshold. This trend suggests that in early stages of economic development, water consumption increases due to expanded economic activities. However, at more advanced stages, technological progress and improved water management contribute to reduced water use, thereby aligning with the EKC hypothesis. Interestingly, the study also reveals that in the industrial sector, the water–GDP relationship follows an inverted 'N'-shape, reflecting a more complex dynamic with multiple phases of increase and decrease in water consumption as income rises[9].

The relationship between water use and economic growth is often explored using the Environmental Kuznets Curve (EKC) framework, which traditionally suggests an inverted U-shaped

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trajectory,where environmental degradation rises with income at early development stages but declines after surpassing a certain economic threshold. While the EKC has been widely applied to pollution, its application to water use reveals more nuanced dynamics. Specifically, water consumption may initially increase with income due to industrial and agricultural expansion, but may later decline as economies adopt more efficient water management practices. As David Katz (2015) notes, applying the EKC to water use suggests that per capita water withdrawals might follow a similar pattern, though sectoral and regional factors can significantly influence the shape and validity of this relationship [10].

2.1.2. Ecological Modernization Theory (EMT)

Circular economy reforms align with Ecological Modernization Theory (EMT) by promoting resource efficiency, waste reduction, and the regenerative use of materials, including water. These reforms seek to decouple economic growth from environmental degradation, directly impacting water use by encouraging practices that minimize both consumption and pollution (Jänicke, 2008).

Within the EMT framework, the adoption of circular economy principles contributes to reduced water demand through technological innovations such as water recycling, reuse, and closed-loop systems. These technologies enhance water efficiency by enabling the treatment and reuse of wastewater across industrial, agricultural, and municipal sectors, thereby decreasing reliance on freshwater sources[11]. Additionally, circular strategies often involve redesigning production processes to reduce water inputs, optimize water cycles, and prevent contaminants from entering natural water bodies [12]; [13].

Ecological Modernization Theory (EMT) emphasizes adopting cleaner technologies and innovative management to reduce water use and pollution. Andersen (2006) highlights market-based tools like water pricing to internalize environmental costs, encouraging efficient and sustainable water management aligned with circular economy principles (Andersen, 2006).

2.2. Hypotheses Development

2.2.1. Economic Factors and Water Demand

The interplay between water use and economic growth has long shown a strong correlation, with Gross Domestic Product (GDP) historically linked to increased resource consumption. However, as global economies evolve, questions surrounding sustainability and efficient resource management become increasingly critical. Traditional methods of measuring water use—such as tracking volume in millions of gallons or cubic meters, are often data-intensive and prone to inconsistencies. To address these challenges, Janez Sušnik (2016) suggests that GDP and GDP-per-capita can serve as effective proxies for predicting water withdrawals. This approach offers a simplified and scalable framework for anticipating resource use trends across different global contexts by aligning economic performance with consumption patterns[14].

Gross Domestic Product (GDP) is a critical economic indicator in water resource economics, as it reflects the overall economic activity and income level of a region or country. A higher GDP is typically associated with increased industrialization and urbanization, which lead to greater water consumption in sectors such as manufacturing, energy production, and urban services. Conversely, in regions with low or stagnant GDP, water demand is generally lower, with a stronger focus on conservation and sustainable use rather than expansion. Furthermore, fluctuations in GDP can influence the affordability and pricing of water, thereby affecting both consumer and industrial behavior. As noted by Oelmann (2007), GDP not only signals economic capacity and development but also shapes water demand patterns, infrastructure investments, and policy priorities[15].

Water use is closely tied to socio-economic development, particularly economic growth measured by Gross National Product (GNP). As noted by Shiklomanov (2000), projections of future water demand often rely on long-term forecasts of demographic and economic trends. Economic

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expansion, especially in developing countries, generally leads to increased water withdrawals across agriculture, industry, and urban sectors.

However, the study emphasizes that improvements in technology and water management practices are expected to enhance water-use efficiency, potentially reducing per capita water consumption even as total water use rises. Population growth, industrialization, and rising energy needs remain key drivers of water demand, but strategic efficiency measures can help offset some of the pressure.

As a conclusion, higher GDP is typically associated with increased water consumption, yet this relationship can be moderated through sustainable planning and innovation in water use [16].

Based on the relationship between economic factors and water demand, the following hypothesis is proposed to investigate their interaction:

H1: *GDP per capita has a significant positive effect on freshwater withdrawals.*

2.2.2. Circular Economy and Water Use

Water withdrawal is classified as a Direct Circular Economy indicator with Non-specific Strategies, meaning it is a measurable aspect relevant to the circular economy but not directly linked to a particular CE strategy such as recycling or material reuse (Moraga et al., 2019). Instead, it reflects broader objectives like resource efficiency and environmental performance, contributing to the overall CE framework without targeting a specific circular pathway.

The authors also highlighted a significant gap in current Circular Economy monitoring frameworks, particularly the European Commission's CE monitoring system, which primarily focuses on macro-level material indicators. Notably, water-specific indicators are absent, despite water's critical role in sustainable resource management. This omission underscores the need to expand CE metrics beyond material flows to include non-material resources like water, ensuring a more holistic and integrated approach to circularity [17]

According to Morseletto, Mooren, and Munaretto (2022), implementing circular economy principles in water management,such as rethinking water use, reducing waste, and enhancing reuse and recycling, can lead to tangible improvements in efficiency, cost-effectiveness, and environmental outcomes. The adoption of strategies like Rethink, Avoid, Reduce, Replace, Reuse, Recycle, Cascade, Store, and Recover not only reduces dependence on freshwater sources but also strengthens ecosystem resilience and aligns with the Sustainable Development Goals (SDGs) [18].

The Water Circular Economy (WCE) shifts from a linear take–make–waste model to sustainable water management focused on reducing consumption, optimizing use, and preserving resources, according to Peydayesh & Mezzenga, (2023). It involves two key principles: decreasing water use through avoidance, reduction, and replacement, and optimizing use via reuse, recycling, and cascading. Progress is tracked using indicators like water stress, water pricing, water use efficiency, and wastewater treatment rates. These strategies aim to close water loops, boost efficiency, and support clean water and sanitation goals [19].

The circular economy redefines resource management by shifting from the traditional model to a system emphasizing continuous use, waste reduction, and closed-loop cycles. In wastewater management, it treats wastewater as a valuable resource rather than mere waste (Kamalsyah, 2024). Key principles include recovering and reusing water, nutrients, and energy, and establishing self-sustaining systems that reduce, reuse, and recycle materials to boost efficiency and minimize environmental harm. This approach fosters innovation in wastewater treatment by focusing on resource recovery, transforming wastewater from a disposal issue into a beneficial asset within economic and ecological systems [20]

Guided by the circular economy approach, we propose the following hypotheses to explore the relationship between *Circular Economy* and water use:

H2: *Circular economy has a significant positive effect on freshwater withdrawals.*

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2.2.3. Climate Resilience and Water Resource Management

Climate change poses a substantial threat to water resources worldwide, demanding urgent attention to adaptive policies and sustainable governance mechanisms. As highlighted by Majahana et al. (2025), climate-induced droughts and increasing water scarcity are already impacting billions globally. By 2050, it is estimated that 57% of the global population, around 5.7 billion people will experience water scarcity for at least one month per year. This escalating crisis is further aggravated by a projected 20–30% increase in global water demand, reaching between 5500 and 6000 km^3 annually. Alongside scarcity, water quality is also deteriorating due to pollution, limiting access to clean and safe water. These challenges intensify competition across sectors such as agriculture, fishing, tourism, energy, and industry, threatening livelihoods and sustainable development. Consequently, robust and climate-resilient water resource management strategies are crucial to mitigate these impacts and ensure long-term water security [21].

According to Muller (2007), climate change is expected to exacerbate weather-related risks for human settlements, including floods and water supply disruptions, making effective water management a critical component of urban resilience. Although mitigation efforts have traditionally received greater emphasis, adaptation strategies are becoming increasingly vital, particularly in climate-vulnerable regions such as sub-Saharan Africa [22].

Tsakiris and Loucks (2023) highlight that climate change poses growing challenges to the management of water, a resource essential for life. Increasing variability in both water quantity and quality, alongside more frequent extreme weather events, underscores the need for adaptive management approaches to ensure water security and preserve environmental integrity [23].

Referring to Eylon Shamir et al. (2015), managing water resources in semi-arid and arid regions poses significant challenges, especially under the pressures of climate change. The Upper Santa Cruz River (USCR) in Arizona serves as a valuable case study, demonstrating how hydrological modeling frameworks can be applied to assess climate change impacts and inform water management strategies [24].

Based on the previous findings, we hypothesize the following:

H3: *Climate resilience has a significant positive effect on freshwater withdrawals*

2.2.4. Demographic Factors and Water Use

Timothy O. Ogunbode et al. (2024) emphasize that the relationship between population growth and water use is critical. In developing countries like Nigeria, rapid population increase intensifies pressure on limited water resources due to urban expansion, agricultural demands, and industrial growth. Factors such as a rise in the number of households, larger family sizes, and increased urbanization directly drive higher domestic water consumption. These dynamics highlight the urgent need for effective planning and sustainable water management strategies to ensure that future water demands can be met efficiently [25].

According to Jain, Lim, Arce-Nazario, and Uriarte (2014), population distribution plays a critical role in shaping water access and management in Puerto Rico, as noted in Molina-Rivera's (1998) 1995 estimates. Rural and mountainous communities with limited treated water and underperforming PRASA infrastructure often adopt coping strategies based on perceptions and resource availability, underscoring the need for targeted interventions [26].

Dorothy F. Dunn and Thurston E. Larson (1963) emphasize that population factors, particularly household size, are key determinants of water use. Larger households tend to have higher total water consumption, with average household size directly influencing overall demand. For instance, households averaging 3.61 persons typically exhibit higher maximum-month water use, while those with five or more members show significantly increased total demand, reflecting the cumulative effect of household population. Although per capita use may vary depending on household composition, homes with more children or multiple members generally consume more water both in total and per capita [27].

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Dupont, Adamowicz, and Krupnick (2010) show that population-related factors, especially household composition, strongly influence water consumption choices in Canada. The presence of children in a household significantly increases the likelihood of using bottled or filtered water instead of tap water, reflecting parental concerns about water quality and health risks. In contrast, the total number of people in a household does not appear to significantly affect preferences between bottled, filtered, or tap water [28].

Based on the evidence presented, we advance the following hypothesis:

H4: *Population has a significant positive effect on freshwater withdrawals.*

Building on the conceptual framework and literature insights, the core hypotheses of this research are consolidated in the following table:

Table 1. Summary of Developed hypotheses.

Code	Hypothesis Statement
H1	GDP per capita has a significant positive effect on freshwater withdrawals.
H2	Circular economy has a significant positive effect on freshwater withdrawals
H3	Climate resilience has a significant positive effect on freshwater withdrawals
H4	Population has a significant positive effect on freshwater withdrawals.

Code	Hypothesis Statement
H1	GDP per capita has a significant positive effect on freshwater withdrawals.
H2	Circular economy has a significant positive effect on freshwater withdrawals
H3	Climate resilience has a significant positive effect on freshwater withdrawals
H4	Population has a significant positive effect on freshwater withdrawals.

3. Data and Methods

3.1. Data Presentation

Table 2. Study Variables and Data Sources.

Type	Variable Name	Definition	Source
Dependent Variable (DV)	Water Use (million m³)	Total freshwater withdrawals (in million cubic meters) in a country	World Bank, 2021
Independent Variable (Control)	Population (people)	Total population of a country in 2021	Eurostat, 2021
Independent Variable (Control)	GDP per Capita (USD)	GDP per capita – an indicator of economic wealth	World Bank, 2021
Independent Variable (Main)	Circular Material Use Rate (%)	Percentage of materials reused – a measure of the circular economy	Eurostat, 2021

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Independent Variable (Main)	ND-GAIN Index (0–100)	Index of climate change resilience and adaptive capacity	Notre Dame Global Adaptation Initiative (ND-GAIN), 2021

Our study uses a set of carefully selected variables to examine the factors influencing national water use. Our dependent variable, Water Use (million m³), measures the total annual freshwater withdrawals in each country, based on World Bank (2021) data. Our control variables capture demographic and economic influences: Population, representing the total number of inhabitants in 2021 (Eurostat), and GDP per Capita, an indicator of economic wealth (World Bank). Our main independent variables focus on environmental performance and adaptive capacity. The Circular Material se Rate (%), sourced from Eurostat, reflects the percentage of materials reused and serves as a proxy for circular economy performance, which may improve water efficiency. The ND-GAIN Index (0–100), from the Notre Dame Global Adaptation Initiative, measures climate change resilience and adaptive capacity, potentially affecting water management strategies. Together, our variables provide a comprehensive framework for exploring how demographic, economic, and environmental factors shape national water use patterns.

The Table 3 presents freshwater withdrawals (in million cubic meters), circular material uses rates (percentage), ND-GAIN climate resilience index scores (0–100), GDP per capita (USD), and population size for 27 European countries in 2021. Values vary widely across countries, with freshwater withdrawals ranging from 0.04 to 33.65 million m³, circular material use rates from 1.3% to 30.6%, ND-GAIN scores between 51.3 and 72.9, GDP per capita spanning approximately $12,000 to over $133,000, and populations ranging from around 500,000 to over 83 million.

Table 3. Secondary data of Freshwater and Socioeconomic Indicators by Country in 2021.

#	Country	Water Use (million m³)	Circular Material Use Rate (%)	ND-GAIN Index (0–100)	GDP per Capita (USD)	Population (people)
1	Romania	7,864	1.3	51.3	14,986.79	19,201,662
2	Ireland	1,581	2.3	64.5	105,561.14	5,066,893
3	Finland	3.000	2.4	72.9	53,099.14	5,533,793
4	Portugal	6.13	2.8	63.0	24,711.45	10,394,297
5	Lithuania	0.25	3.9	61.7	23,934.73	2,810,761
6	Bulgaria	5.08	4.9	55.0	12,274.08	6,532,117
7	Latvia	0.18	5.0	60.8	20,654.70	1,893,223
8	Greece	10.22	5.2	59.5	20,654.70	10,678,632
9	Cyprus	0.24	5.4	58.1	33,734.29	914,476
10	Hungary	4.67	5.9	57.1	18,755.10	9,651,461
11	Croatia	0.67	6.2	55.4	17,789.93	3,893,026
12	Poland	9.27	7.5	61.6	18,635.51	37,073,357
13	Spain	29.02	8.5	61.9	30,817.68	47,400,798
14	Slovenia	0.93	8.8	63.9	29,187.37	2,108,977
15	Denmark	0.98	9.1	71.1	69,727.99	5,840,045
16	Sweden	2.48	9.9	69.9	61,174.97	10,379,295
17	Luxembourg	0.05	10.2	67.3	133,711.79	634,730
18	Slovakia	0.57	10.6	57.9	22,138.19	5,459,781

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19	Czechia	1.35	12.8	64.7	27,696.46	10,494,836
20	Germany	25.79	13.9	69.5	52,265.65	83,155,031
21	Austria	3.14	14.3	69.0	53,648.72	8,932,664
22	France	24.67	17.6	67.7	43,725.10	67,728,568
23	Estonia	1.00	18.1	64.5	27,953.77	1,330,068
24	Belgium	4.22	19.7	63.5	51,655.79	11,554,767
25	Malta	0.04	19.8	59.2	38,027.38	516,125
26	Italy	33.65	20.8	59.6	36,852.54	59,236,213
27	Netherlands	7.95	30.6	66.0	60,141.99	17,475,415

3.2. Methods

This study employs a Multiple Linear Regression (MLR) approach to analyze the determinants of national water use across European countries in the year 2021. The analysis is cross-sectional, focusing on data collected at a single point in time to examine relationships between water use and key demographic, economic, and environmental factors.

We utilized secondary data sourced from Eurostat and the World Bank, ensuring the data's reliability and comparability across countries. Specifically, variables included total freshwater withdrawals (dependent variable), population size, GDP per capita, circular material use rate, and the ND-GAIN Index, which measures climate resilience and adaptive capacity.

All data were compiled and analyzed using IBM SPSS Statistics version 27 . The Multiple Linear Regression models controlled for potential confounding variables to isolate the effects of the main independent factors on water use.

No new experimental protocols were developed in this study. All methods applied are well-established and have been appropriately cited.

The general form of the MLR model is:

$$Yi = \beta 0 + \beta 1 X1i + \beta 2 X2i + \beta 3 X3i + \beta 4 X4i + \varepsilon i \ (1)$$

Y = Water Use (million m^3)
$X1$= Population (people)
$X2$= GDP per Capita (USD)
$X3$ = Circular Material Use Rate (%)
$X4$ = ND-GAIN Country Index (0–100)
εi = Error term

4. Results

4.1. Descriptive Statistics

Table 4. Summary of Descriptive Statistics.

Statistics						
		Water Use (million m³)	Circular Material Use Rate (%)	ND-GAIN Index (0–100)	GDP per Capita (USD)	Population (people)
N	**Valid**	27	27	27	27	27
	Missing	0	0	0	0	0
Mean		6,851	10,277	62,837	40870,99815587965000	16514481,89

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Median	3,00	8,8000	63,000	30817,68285590	8932664,00
Std. Deviation	9,672	7,107	5,3285	9223,372036854	22262590,262
Range	33,605	29,300	21,6	121437,7168409	82638906
Minimum	,0395	1,3000	51,3	12274,07759504	516125
Maximum	33,645	30,600	72,9	133711,7944359	83155031

The descriptive statistics for the 27 European countries in 2021 reveal considerable variability in the key variables studied. Freshwater withdrawals range widely, with an average of 6.85 million m^3 and a standard deviation of 9.67, indicating a right-skewed distribution, some countries withdraw significantly more water than others. The median value of 3 million m^3 confirms this skewness, suggesting that most countries consume less than the average, while a few large users raise the mean.

The circular material use rate shows an average of 10.28%, with values spanning from 1.3% to 30.6%, pointing to stark differences in circular economy adoption across Europe. The median rate of 8.8% again confirms a skewed distribution, highlighting that many countries are still in the early stages of implementing circular material use strategies.

In terms of climate resilience, measured by the ND-GAIN Index, the average score is 62.84 with relatively low variability (standard deviation = 5.33). This suggests a generally high and consistent level of climate adaptive capacity across European nations.

4.2. Multiple Linear Regression Model Summary

Table 5. model summary.

Model	R	R Square	Adjusted R Square	Standard Error of the Estimate	Durbin-Watson
1	0.931	**0.867**	0.843	3.83447	2.190

The GDP per capita variable exhibits strong disparities, with a mean of approximately $40,871 and a range extending from $12,274 to $133,712. The high standard deviation ($9,223) and skewed distribution reflect significant economic inequality, with a few wealthy nations raising the regional average. Similarly, population size varies widely, from less than a million to over 83 million, with a mean of 16.5 million and a standard deviation of 22.26 million, underscoring major demographic differences among the countries in the sample.

The multiple linear regression model developed to explain water consumption (WATER_USE_MMC) based on the independent variables, namely population (Eurostat Population 2021), GDP per capita (2021), circular material use rate (Eurostat Circular Material Use Rate 2021), and the ND-GAIN Index (ND-GAIN Country Index 2021) demonstrates strong statistical performance.

The multiple correlation coefficient (R) reaches 0.931, indicating a very strong correlation between the predictors and the dependent variable. The coefficient of determination (R^2) is 0.867, meaning that 86.7% of the variance in water consumption is explained by the model's variables. This result remains high even after adjustment (Adjusted R^2 = 0.843), showing that the model remains relevant even when accounting for the number of variables included.

The standard error of the estimate is 3.83, representing the average deviation between predicted and observed values. Finally, the Durbin-Watson statistic has a value of 2.190, suggesting no significant autocorrelation in the model's residuals.

These results indicate that the model is statistically robust and provides reliable predictions of water consumption based on the considered factors.

 doi:10.20944/preprints202508.1002.v1

4.3. ANOVA Summary for Multiple Linear Regression Model

Table 6. ANOVA Summary.

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	2108.768	4	527.192	35.856	.000
Residual	323.470	22	14.703		
Total	2432.238	26			

The analysis of variance (ANOVA) assesses the overall significance of the regression model. The results show a regression sum of squares of 2108.768 with 4 degrees of freedom, compared to 323.470 for the residuals (errors) with 22 degrees of freedom, for a total of 2432.238. The mean square for regression is 527.192, while that for the residuals is 14.703. The F-test statistic reaches a high value of 35.856, with a p-value less than 0.001 (Sig. < 0.001). This indicates that the regression model is highly significant as a whole. In other words, the explanatory variables included (population, GDP per capita, circular material use rate, and ND-GAIN index) contribute statistically significantly to predicting water consumption (WATER_USE_MMC).

4.4. Regression Coefficients, Multicollinearity Diagnostic and Hypotheses Testing

Table 7. Regression Coefficients.

Model	Unstandardized Coefficients	Standardized Coefficients	t	Sig.	Tolerance	VIF
	B	Std. Error	Beta			
(Constant)	14.835	10.567		1.404	0.174	—
Eurostat Circular Material Use Rate 2021	0.047	0.114	0.035	0.411	0.685	1.167
ND-GAIN Country Index 2021	-0.248	0.184	- 0.137	-1.348	0.191	1.699
GDP per capita 2021	0.000009563	0.000	0.028	0.278	0.783	1.633
Eurostat Population 2021	0.0000004069	0.000	0.937	11.215	0.000	1.154

The analysis of the coefficients from the multiple regression model allows for assessing the individual effect of each independent variable on water consumption (WATER_USE_MMC), while controlling for the other factors. Among the four variables, only population (Eurostat Population 2021) shows a significant effect, with an unstandardized coefficient of 4.069E-7 and a t-statistic of 11.215 ($p < 0.001$). This indicates that population is a major and significant factor in explaining water consumption, with a strong standardized coefficient (Beta = 0.937), reflecting a dominant effect.

The other variables, circular material use rate (2021), ND-GAIN index, and GDP per capita (2021), do not show statistically significant effects, as indicated by their respective p-values (0.685, 0.191, and 0.783), all above the 0.05 significance threshold. Therefore, their explanatory contributions in this model are limited.

Regarding multicollinearity, tolerance values are all above 0.5, and variance inflation factors (VIF) are all below 2, indicating no problematic multicollinearity among the independent variables. Thus, the model is statistically robust and reliable, with population emerging as the principal determinant of water consumption in this dataset.

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The following regression equation models the relationship between freshwater withdrawals and the selected predictor variables:

$$\text{WATER}_{\text{USE}_{\text{MMC}}}. = 14{,}835 + 0{,}047 \times (\mathit{Circular\ material\ use\ rate}) - 0{,}248 \times (\mathit{ND - GAIN\ Index}) + 9{,}563 \times 10 - 6 \times (\mathit{GDP\ per\ capita}) + 4{,}069 \times 10\hat{} - 7 \times (\mathit{Population}) \quad (2)$$

The results presented in Table 8 indicate that among the four hypotheses tested, only H4, which posits that population size has a significant positive effect on freshwater withdrawals, is supported by the data. The regression analysis reveals a strong and statistically significant positive relationship between population and water use ($p < 0.001$), suggesting that countries with larger populations tend to withdraw more freshwater.

Table 8. Hypotheses Testing Results Summary.

Hypotheses	Predictor Variable	Effect Direction	Significance (p-value)	Result
H1: GDP per capita has a significant positive effect on freshwater withdrawals.	GDP per Capita	Positive (β = 0.028)	0.783 (Not significant)	Not supported
H2: Circular economy practices have a significant positive effect on freshwater withdrawals.	Circular Material Use Rate (%)	Positive (β = 0.035)	0.685 (Not significant)	Not supported
H3: Climate resilience has a significant negative effect on freshwater withdrawals.	ND-GAIN Index	Negative (β = -0.137)	0.191 (Not significant)	Not supported
H4: Population size has a significant positive effect on freshwater withdrawals.	Population	Positive (β = 0.937)	0.000 (Significant)	Supported

4.5. Normality of Residuals Assessment

Table 9. Normality of residuals Test.

Normality Test						
	Kolmogorov-Smirnova			Shapiro-Wilk		
	Statistics	ddl	Sig.	Statistics	ddl	Sig.
Standardized Residual	,217	27	,002	,899	27	,613

In contrast, hypotheses H1, H2, and H3, which predicted significant effects of GDP per capita, circular economy practices, and climate resilience, respectively, were not supported. Although the directions of their effects align with expectations, these predictors were not statistically significant at conventional levels ($p > 0.05$). This finding suggests that, based on the 2021 cross-sectional data for European countries, economic wealth, circular material reuse, and climate resilience do not exert a clear or strong direct influence on freshwater withdrawals.

In general, these findings highlight population size as the primary driver of water use in this context, while indicating that other factors may require further investigation or alternative analytical approaches to better understand their potential impacts. The Kolmogorov-Smirnov test with Lilliefors correction shows a statistic of 0.217 and a p-value of 0.002, suggesting a rejection of the normality hypothesis ($p < 0.05$). In contrast, the Shapiro-Wilk test yields a statistic of 0.899 with a p-value of 0.613, indicating that the normality hypothesis cannot be rejected ($p > 0.05$).

Since the Shapiro-Wilk test is generally considered more reliable for small samples (here n = 27), we can conclude that the standardized residuals follow a normal distribution. This normality of residuals supports one of the fundamental assumptions required for the validity of statistical tests (t, F) in linear regression.

4.6. Homoscedasticity Assessment

Table 10. Homoscedasticity tests.

Test	LM Statistic	Degrees of Freedom (df)	p-value (Sig.)	Conclusion
Breusch-Pagan	0.520	1	0.471	Homoscedasticity (No heteroscedasticity)
Koenker (robust BP)	0.285	1	0.594	Homoscedasticity (No heteroscedasticity)

The Breusch-Pagan and Koenker tests were conducted to check the assumption of homoscedasticity of the regression model residuals. The results show that the Breusch-Pagan LM statistic is 0.52 with a p-value of 0.471, while the Koenker statistic is 0.28 with a p-value of 0. 594.Since both p-values are greater than the 0.05 significance level, we do not reject the null hypothesis of homoscedasticity. This indicates that the variance of the residuals is constant across different values of the explanatory variables, and there is no evidence of heteroscedasticity in the model. Therefore, the conditions for using classical linear regression are met with regard to the variance of the errors.

4.7. Summary of Model Diagnostics

Table 11. Model Diagnostics.

Aspects	Results
Model Fit	Adjusted $R^2 = 0.843$ (84.3% variance explained)
Model Significance	$F(4,22) = 35.856$, $p < 0.001$ (significant)
Linearity	Verfied (supported by residual plots)
Independence of Errors	Durbin-Watson = 2.19 (no autocorrelation)
Multicollinearity	VIFs < 2 (no multicollinearity)
Normality of Residuals	Shapiro-Wilk p = 0.613 (normal distribution)
Homoscedasticity	Breusch-Pagan p = 0.471, Koenker p = 0.594 (constant variance)

The Multiple Linear Regression model demonstrates a strong fit, explaining 84.3% of the variance in freshwater withdrawals among European countries. The model is statistically significant overall, confirming that the predictors collectively relate meaningfully to water use. Key assumptions,including linearity, independence of errors, absence of multicollinearity, normality of residuals, and homoscedasticity,are adequately met, supporting the validity of the model's results. However, among the tested predictors, only population size shows a statistically significant positive effect on freshwater withdrawals, indicating it as the primary driver in this context. Other variables such as GDP per capita, circular economy practices, and climate resilience did not significantly influence water use in this analysis.

5. Discussion

Our study highlights population size as the primary driver of freshwater withdrawals across European countries, supporting the critical link between demographic growth and water demand emphasized by Timothy O. Ogunbode et al. (2024). In line with their findings in developing contexts

 doi:10.20944/preprints202508.1002.v1

like Nigeria, increasing population intensifies pressure on water resources through expanding households, urbanization, and agricultural needs. This underscores the urgent need for policymakers to incorporate demographic trends into water resource planning and infrastructure investment to ensure sustainable supply.

Contrary to expectations, our analysis did not find significant effects for GDP per capita, circular economy practices, or climate resilience on water withdrawals. While GDP traditionally correlates with resource consumption due to industrialization and urbanization (Oelmann, 2007; Sušnik & Hettiarachchi, 2016), its predictive power may be moderated by varying efficiency levels, conservation policies, or economic structure differences across countries. This suggests that economic growth alone is not a reliable predictor of water use, highlighting the potential for decoupling water demand from economic expansion through improved efficiency and regulation.

Regarding circular economy approaches, previous literature frames the Water Circular Economy (WCE) as a transformative paradigm shifting resource management from linear to closed-loop systems (Peydayesh & Mezzenga, 2023; Kamalsyah, 2024; Abid et al., 2024). Principles such as reducing consumption, recycling, and resource recovery aim to improve efficiency and align with Sustainable Development Goals (Morseletto et al., 2022). The absence of a significant effect in our cross-sectional study may reflect the nascent stage of implementation, varying adoption rates, or limitations in current indicators to capture nuanced water reuse and recycling practices at the country scale. This highlights the importance of accelerating circular economy initiatives and developing better metrics to evaluate their impact on water sustainability.

Climate resilience, captured by the ND-GAIN index, may influence water use indirectly or over longer periods than our 2021 snapshot allows, suggesting the need for longitudinal studies to assess adaptation impacts more effectively. Investing in adaptive infrastructure and governance remains essential to prepare for future climatic variability and water security challenges.

Limitations include the cross-sectional design limiting causal inference, potential measurement constraints in circular economy and resilience proxies, and unmeasured confounders such as water pricing policies or technological innovations. Future research could employ panel data to explore temporal dynamics, integrate more detailed sector-specific water use data, and investigate policy impacts to better understand drivers of water sustainability.

In sum, our findings emphasize demographic factors as critical in freshwater demand, while encouraging deeper exploration of economic and environmental mechanisms shaping sustainable water management across diverse contexts.

6. Conclusions

This study demonstrates that population size is the primary determinant of freshwater withdrawals across European countries, underscoring the importance of demographic factors in water resource management. While economic wealth, circular economy practices, and climate resilience are important considerations, they did not show significant direct effects in the 2021 cross-sectional analysis. These findings highlight the need for targeted water policies that address population-driven demand and promote sustainable consumption patterns. Future research should explore temporal changes, sector-specific dynamics, and more detailed indicators of circular economy implementation and climate adaptation to better inform integrated water management strategies.

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