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Spatial analysis of water quality and income in Europe

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ABSTRACT

The purpose of this study is to empirically investigate the environmental Kuznets curve (EKC) relationship between water quality and income within the European Union, considering spatial interdependences across countries. To this end, we apply a spatial econometrics framework using panel data, at the national level, for twenty EU countries across seventeen years, 1998 to 2014. Furthermore, we account for the role of human and livestock population size, institutional quality and economic openness for water quality. Results show that a significant EKC relationship is seen with an inverted *N*-shaped relationship between income and water quality. Water quality is decreasing in income for low income levels, increasing in income when GDP per capita for medium income levels, and deteriorating for high income levels. Eight out of twenty countries have income levels associated with a declining water quality. Spatial spillovers between countries are significant. Higher livestock density levels are associated with lower levels of water quality, while institutional quality and openness to trade are positively associated with water quality.

1. Introduction

Good water quality is crucial to human health, social and economic development as well as the functioning of ecosystems [1]. Economic activities, unabated population growth and unsustainable farming practices further increase pressures on water bodies [2,3]. This poses a direct threat to the survival of marine life, health risks to human and animal populations near bodies of water as well as tourism. However, these pressures can be counteracted through restrictions on polluting activities and improved wastewater management. The European Union (EU) adopted the so-called Water Framework Directive (WFD) (2000/60/EC) in the year 2000 to ensure that the Member States achieve good ecological status in all surface water bodies. Despite progress, only 40% of surface water bodies currently meet this requirement [3]. This raises a concern regarding the potential of policy changes to counteract the increasing scale of production and consumption, with respect to the impact on water quality.

Income is seen as a major driver of human impact on water quality. In earlier literature, the relationship between income and water quality is frequently analysed using the so-called Environmental Kuznets Curve (EKC) approach [33,34]. Essentially, an EKC relationship would be found if, during the first stages of economic growth, water quality degrades with higher income as policymakers and households are more concerned with higher material output than with environmental quality. With technological improvements and increasing knowledge, associated with later stages of industrialization, economic growth increases along with greater awareness as to

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the effects on the environment [4]. This increases governmental and industrial efficiency, and leads to more stringent environmental policies, which results in an increase in environmental quality [5,6]. Together this suggests an inverted U-shaped relationship between income and environmental degradation.

In previous literature, several studies have investigated whether an EKC relationship exists for water quality. Archibald et al. [7] and Lee et al. [5] examine the EKC hypothesis across European countries using panel data, with biological oxygen demand (BOD) levels in water bodies as a proxy for water quality. Gassebner et al. [8] also considers BOD levels across a panel data set across 120 countries. These studies both find that an EKC relationship is supported. A couple of studies extend on the analysis by applying a spatial framework, motivating this choice by the spatial overlap of natural watershed boundaries with administrative borders. Farzin and Grogan [9] use a spatial approach while also allowing for a potentially N-shaped relationship between income and water quality degradation. Applying their study in the context of California, and considering 24 water quality variables, their results confirm the existence of an N-shaped EKC, when using ammonia and fecal coliform bacteria as indicators of water quality. Spatial spillover effects are observed through spatial autocorrelation of water quality between neighbouring counties. Paudel et al. [10] also examine the EKC relationship using a spatial approach, considering nitrogen, phosphorus and dissolved oxygen levels across Louisiana counties. They assumed that weighted income in neighbouring counties positively impacts water quality, but results did not show a significant spatial effect. In addition to income, many EKC studies also account for several other factors that potentially affect water quality, including population density, for which results are mixed, and agricultural activity, where results indicate a negative impact on water quality [9]. Furthermore, Archibald et al. [7] and Gassebner et al. [8] find that economic and trade liberalization positively affects water quality. A summary of the main findings, including turning points, can be found in Table 1.

The main objective of this paper is to empirically investigate the relationship between water quality and income across EU countries over the time period 1998 to 2014. To this end, we use the EKC approach and a spatial econometric framework. The first aim is to identify whether an N-shaped EKC exists, rather than an inverted U-shape. An N-shaped curve could potentially explain the slow progress towards WFD targets for good ecological status. Controlling for spatial effects is necessary to avoid biased estimates. Given the larger spatial scale of our study, compared to Farzin and Grogan [9] and Paudel et al. [10], the argument for overlaps between watershed boundaries and administrative units is not equally strong. Instead, spatial effects across countries could arise due to institutional learning, or strategic behavior by governments (Fredriksson and Millimet, 2003). Of course, the very transboundary nature of water bodies could likely induce spillovers, but the exact nature and strength of this dynamic is an empirical issue. Earlier results from EKC studies applied to air-borne emissions in Europe suggest that positive spatial correlations could be expected among the EU countries [11,12], consistent with institutional learning rather than strategic behavior. Given the importance of human settlements and livestock density for water quality [2,3,13], we also control for those factors.

The remainder of the paper is structured as follows. In Section 2, we provide a more detailed background and present the hypotheses. In Section 3, we outline the econometric method and provide a description of the data. Section 4 presents the results from the analysis, and Section 5 provides a discussion and conclusions.

2. Background and hypotheses

Water pollution is characterized by spatial heterogeneity, as the impact of pollution on a recipient depends on the location of the emission source. Moreover, recipients vary in their sensitivity to pollution. Policies for water quality increasingly recognize the spatial perspective. This was an important factor in determining the design of the WFD, where it is recommended that policies are developed on the catchment level [3,14]. In the following we outline our conceptual approach, describing the linkages between water quality and income, the role of spatial spillovers, emission sources and institutions.

2.1. The relationship between income and water quality

Despite policy reforms permitting tailoring water pollution policy to the local context, and increasing income, it remains unclear whether European countries will succeed to achieve good water quality. The capacity of currently regulated pollution abatement measures is often not sufficient for meeting set water quality targets. Furthermore, adding additional measures can be highly expensive [15]. Also, institutional constraints can imply that policy costs substantially exceed those for a least cost policy, which risks leading to difficulties to obtain political support for stringent policies [[34,38]]. Hence, technical capacity constraints in combination with institutional inefficiencies can imply that raising income will not be sufficient for solving water quality problems. It is therefore argued in the literature that a cubic relationship between real GDP per capita and water quality could be motivated, rather than a quadratic relationship which is otherwise more common in EKC studies. The assumption of cubic relationship allows for the possibility that improved water quality during the process of economic growth is only temporary and is eventually followed by a downturn in water quality for high income levels [9,16,17].

2.2. Spatial spillovers

Watersheds and bodies of water are not confined within a country's boundaries; instead, they often span more than one country as

Table 1
Turning points, and analysis of spatial effects, in EKC studies applied to water quality.

Source	Region	Significance (EKC)	Significant spatial effects	Turning point(s) (USD)
[7]	Europe and Commonwealth of Independent States	Yes	N/A	3,800–5,000 (BOD)
[5]	Europe	Yes	N/A	38,221 (BOD)
[8]	120 countries	Yes	N/A	26,800 (BOD)
[10]	Louisiana, USA	Yes	No	10,241–12,993 (N) 6,636–13,877 (P) 6,467–12,758 (DO)
[9]	California, USA	Yes	Yes	36,774 and 63,370 (NH4) 38,298 and 59,794 (fecal coliform)

well as produce economic, environmental and institutional[1] spillover effects between countries [9,17–19]. A trend of recent EKC literature has been inclusion of spatial interaction effects, where studies argue that its omission can lead to biased and/or inconsistent EKC estimates arising from model misspecification [7,20–22]. In practical policy, catchment and administrative boundaries often overlap, implying that we can expect to see a correlation in environmental outcomes across jurisdictions. Moreover, several studies on the EKC show that countries that improve their regulatory frameworks tend to positively influence the institutions and environmental performance of their neighbours through reduced spillovers and encouraging others to develop their own institutional quality [11,23]. The spatial pattern can also be affected by strategic interaction in environmental policy, driven by the aim of policymakers to attract labour and industry, and enhance the likelihood of re-election (Fredriksson and Millimet, 2003).

2.3. Population and livestock density

Water quality is influenced by population and livestock density through runoffs of nutrients [2,3,24,25]. Higher population densities put heavier burdens on the water environment through higher discharges in industrial and domestic wastewater [26,27]. On the other hand, a high population density implies that many people are concerned with water quality conditions, which can imply a greater willingness-to-pay for measures to improve water quality, and that policymakers are put under more pressure to undertake improvements [7,16,28,29]. In addition, high population density implies scale economies in wastewater infrastructure, which also tends to counteract the negative impact on water quality. Hence, the net effects of population density are ambiguous albeit empirically, Farzin and Grogan [9] finds a negative impact on water quality.

Intensive livestock farming is known to be a significant source of organic water pollution [24]. We follow earlier EKC studies on water quality by accounting for the impact of livestock [6,19], noting that a significant and negative relationship with water quality was found in, e.g., Farzin and Grogan [9].

2.4. Impact of institutional quality and openness to trade

The development of countries towards a higher institutional quality and increased openness of the market can potentially affect water quality. The European Union explicitly states that the strengthening of institutional quality in terms of transparency, effective regulation and public participation, as well as improving openness to foreign investors and trade, is an important tool to development which may enhance water quality [13,30]. As stated by Moss [31], the success of water policies, such as the WFD, depends on the degree of 'fit' with existing institutional structures and practices. In that respect, the WFD lays emphasis on cooperation between government units across different sectors and levels, transparency and public participation.

2.4.1. Institutional quality

As countries develop, this is typically associated with increased economic and social freedom, better transparency, higher public participation and increased accountability. This can positively affect environmental quality. It is deemed difficult to enforce the WFD and ensure appropriate solutions in parts of Europe where effective political pressure and legislation are lacking [32]. The link between institutional quality improvements and environmental quality is argued to be weaker in less developed countries, where improvements in institutions may prioritize other policy targets [33,34]. Several studies show, empirically, that improvements in institutional quality are correlated with improved environmental performance [18,23]. However, it is not always the case that such links can be shown. For example, Woodhouse and Muller [35] find that public participation and environmental policy effectiveness are only occasionally associated.

2.4.2. Trade and investment openness

Several EKC studies account for the effect of openness to trade and foreign direct investment (FDI) (Fang et al., 2018; [19]. Such openness can lead to higher welfare, increasing the demand for environmental quality, and increased technology transfers that can improve environmental conditions [36]. Hence, ignoring openness to trade and FDI may lead to model misspecification which

[1] Institutional spillovers can include, for example, governments learning from or mimicking neighbours' choice of technologies, policy instruments and enforcement practices.

potentially biases the estimated results [37]. However, the previous EKC literature has presented mixed evidence regarding openness to trade and FDI. Fang et al. (2018), considering industrial wastewater in China, states that trade openness may improve environmental quality only if it leads to a modernization of the capital stock which can outweigh the increased consumption that follows with trade.

On the other hand, it is also argued that economic and trade liberalization may harm the environment in low-income countries, for example if polluting sectors relocate to low income countries that try to attract investment by providing relatively more slack environmental regulation [38], where the textile industry is argued to be one example of this [39]. This ambiguity is illustrated by results in Naughton [37], showing a significant spatial effect from trade and FDI for Europe, which either improves or worsens environmental quality depending on the level of environmental regulation and scale effects. Below, we control for the effect of increased trade and investment openness on water quality.

3. Methodology

We aim to identify an EKC relationship for water quality within Europe, taking into account the possible spatial effects relevant to this relationship. To conduct a spatial econometric analysis, the first step is to test for spatial autocorrelation in the dependent variable for water quality within the countries. Following this, we conduct tests to determine the appropriate econometric method. This section describes these tests, the econometric model as well as the descriptive features of the data.

3.1. Tests for spatial dependence

Two sets of tests are used to test for spatial autocorrelation within the dependent variable – the classical global Moran's I and Geary's C [40,41]. Even though Moran's I test is seen as more robust than Geary's C, both are included to ensure robustness [22]. 'Global' here refers to a spatial dependence matrix across the entire geographic region under study, in this case Europe. Test results fall between -1 and 1 and tends to zero when no spatial autocorrelation is found. Positive values indicate positive spatial autocorrelation where similar values occur spatially near one another; negative values indicate negative spatial autocorrelation where dissimilar values occur geographically close.

To conduct these tests, an appropriate spatial weight matrix is created, denoted by $\mathbf{W}$, which is a first-order contiguity $n\times n$ matrix that characterizes the degree of spatial dependence of the studied spatial units within the geographical region of interest. The weight matrix has diagonal elements equal to zero so that a country cannot be its own neighbour and w_{ij} elsewhere, where $w_{ij}=1$ if i and j are neighbours and $w_{ij}=0$ if otherwise [42].

In this study, the spatial weight matrix used in our baseline empirical estimations focuses on the k-nearest neighbours of each country. Here, six separate weight matrices are created from $k=1,\ldots,6$ nearest neighbours. The weights in each matrix are then row standardized such that the sum of the elements equals one which ensures that relative, not absolute, distance matters [43]. In the robustness analysis, alternative spatial matrices are used, considering distance as well as upstream – downstream relationships between countries that share common water bodies.

3.2. Tests for econometric method selection

Following standard practice in applied spatial econometric literature [42,44], we begin with a non-spatial pooled ordinary least squares (OLS) regression model, which is used as a baseline, and is given below in Equation (1):

$$y_{it}=\alpha+\mathbf{X}_{it}\beta+\varepsilon_{it};\quad \varepsilon_{it}\sim N\left(0,\sigma^2\right) \tag{1}$$

where α is the intercept and $\mathbf{X}_{it}$ a vector of explanatory variables and its associated parameters (β) for cross-section i at time t.

Following this, we test for the possibility to extend the baseline model to include spatial interaction effects. As discussed in section 2, there may exist spatial dependence not only in the dependent variable (water quality) but also in the explanatory variables. We may then expand the baseline model using a general specification for static spatial panel models to include these effects as shown in Equation (2).

$$\begin{aligned} y_{it} &= \tau_n\alpha_i+\lambda W_{ij}y_j+\mathbf{X}_{it}\beta+\theta W_{ij}\mathbf{X}_{it}+\xi_i+\psi_t+\mu_{it} \\ \mu_{it} &= \rho W_{ij}\mu_{it}+\varepsilon_{it};\quad \varepsilon_{it}\sim N\left(0,\sigma^2\right)\quad i=1,\ldots,n;\quad t=1,\ldots,T \end{aligned} \tag{2}$$

where $\mathbf{y}$ is the vector for the dependent variable for each unit of the sample $i=1,\ldots,n$; τ_n is the $n\times k$ vector of ones for the constant term α and β; and θ are the $k\times 1$ vector of parameters associated with the $n\times k$ matrix of explanatory variables and the spatially explicit explanatory variables, respectively. These explanatory variables include the natural logged (ln) values of GDP (lnGDP), the squared and cubed values of this natural log, $(\ln\text{GDP})^2$ and $(\ln\text{GDP})$,[3] the logged values of population density (lnPopDens) and livestock density (LiveDens), governance indicators (GovInd), trade openness (Trade), as well as openness to foreign direct investment (FDI). The variables ρ and λ denote the spatial autoregressive (or lag) and the spatial autocorrelation coefficients, respectively. The parameters ξ_i and ψ denote the spatial-specific and time fixed effects. Finally, ε denotes a vector of disturbance terms such that $\varepsilon = (\varepsilon_1, \dots, \varepsilon_n)^T$ where ε_i is assumed to be independently and identically distributed for all i with a mean of zero and a variance of σ^2.

Using the spatial weight matrices detailed in section 3.1, we run the classical Langrage Multiplier (LM) (Anselin, 1988) and the robust-LM (RLM) (Anselin et al., 1996) tests on the residuals of the estimated OLS model. These tests indicate if we can reject the OLS specification in favour of the spatial error (SEM) or spatial lag (SAR) model. If we reject the OLS model in favour of both the SEM and SAR models, this suggests that a spatial Durbin model is appropriate. These results are detailed within section 4.2.

Given the tests for econometric model selection, we can write the spatial lag model (i.e. where $\theta = 0; \quad \rho = 0$ in equation (3)) as:

$$y_{it} = \lambda W_{ij} y_{j_t} + \mathbf{X}_{it}\beta + \xi_i + \varepsilon_{it}; \quad t = 1, \dots, T \tag{3}$$

All variables are as previously defined. The spatial autoregressive coefficient is given by λ to which a statistically significant result would indicate a sizeable intensity of spatial interdependency. Including the explanatory variables contained in the vector $\mathbf{X}_{it}$, we have the following specification (equation (4)) which also includes a time trend.

$$\begin{aligned} y_{it} = {} & \lambda W_{ij} y_{j_t} + \beta_1 \ln GDP_{it} + \beta_2 (\ln GDP_{it})^2 + \beta_3 (\ln GDP_{it})^3 + \beta_4 \ln PopDens_{it} \\ & + \beta_5 LiveDens_{it} + \beta_6 GovEff_{it} + \beta_7 \ln Trade_{it} + \beta_8 FDI_{it} + Time_t + \xi + \varepsilon_{it} \end{aligned} \tag{4}$$

Given the above equations and if an EKC relationship is seen, the turning points are calculated to determine the real GDP per capita range to which water quality would begin to improve.

3.3. Data description

Our dependent variable for water quality is given through the measure of the oxygen content within bodies of water. The oxygen content is one of the major indicators used to evaluate ecological status according to the WFD [3]. If the oxygen level is too low, this can affect the composition of aquatic species communities, and reduce fish stocks. Hence, the oxygen level is crucial for the delivery of surface water ecosystem services. The oxygen content is determined by natural conditions as well human activities causing nutrient emissions from point and nonpoint sources and soil erosion. The WFD also considers additional water quality indicators such as phosphorus and nitrogen concentrations. However, oxygen contents data show a considerably better coverage across time and countries compared to the nutrient related measures, which motivates our choice to focus on this variable. Still, it can be noted that nutrient levels are negatively related to oxygen levels, as nutrient emissions lead to excessive growth of plants and algae which, when decaying, consume oxygen and therefore cause oxygen deficiency.

This study constructs a balanced panel data for 20 countries[2] within the European Union over the years 1998–2014 where data is on an annual basis. The choice of countries to include was determined by the availability of a sufficiently long time series of data, including also data for recent years, for the dependent variable.[3]

Considering the oxygen content within bodies of surface water (Oxy),[4] our data are median values measured in mg/l and are collected from the European Environment Agency's (EEA) [45] database (Waterbase) for each country apart from Sweden to which data is provided by the MVM Database [46] which is constructed by the Swedish University of Agricultural Sciences. Waterbase contains water quality data, which was delivered by the Member States countries and cooperating countries.[5] The purpose of Waterbase is to provide indicators for the assessment of state and trends in water quality and to monitor the progress of European policy objectives. The fact that the data are regularly used for policy evaluation supports their relevance in our analysis. Still the dataset has limitations: although the EU increasingly demands harmonization of environmental monitoring, monitoring schemes could potentially vary across countries, for example the frequency of sampling might differ. Also, it could be possible that within a given country, some regions are subject to more intensive monitoring than others. Together, this motivates us to use of the median values of the dependent variable across all surface water monitoring stations. The median is a more representative measure of the distribution in this situation, as the role of outliers is reduced.

Income is measured as real GDP per capita, given in constant 2010 US dollars [47]. Population density (PopDens) is measured by population per square kilometre [48]. Livestock density (LiveDens) is calculated by using total livestock data [49], which we

[2] Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Slovakia, Spain, Sweden and United Kingdom.

[3] For example, data on oxygen content for Hungary was available for 1987–2007, which is a long time period. However, data before 1998 was available for few other countries. Hence, Hungary was excluded from the analysis due to the lack of data for recent years and difficulties to match the time series with the other countries. As another example, oxygen data for Portugal were only available for 2006–2012, motivating exclusion of Portugal in the analysis.

[4] Due to issues of missing data, where in total 304 out of 340 observations are given from oxygen content levels, linear inter- and extrapolation is used in order to conduct spatial analysis. A table for data description of the non-extrapolated data is provided in Supplementary Appendix A, Table SA1.

[5] The countries report these data within the scope of the current WISE SoE - Water Quality ICM (WISE-6) reporting obligation and the retired WISE SoE - Water Quality (WISE-4), River quality (EWN-1), Lake quality (EWN-2) and Groundwater quality (EWN-3) reporting obligations.

recalculated as livestock units using coefficient provided by Eurostat [49] and shown in Supplementary Appendix (Table SA2). We then calculated the number of livestock units per square kilometre, which was used in the regressions.

The Worldwide Governance Indicators (WGI) are provided by the World Bank [50] which detail the level of institutional quality. In particular, they detail four key variables: 1) Voice and accountability (Voice), 2) Government effectiveness (GovEff), 3) Regulatory Quality (Reg), 4) Control of Corruption (Corrup), and 5) Rule of Law (Law). These indicators are measured on a scale from −2.5 (weak governance) to 2.5 (strong governance). Due to missing data for the years 1999 and 2001, linear interpolation is used to ensure a balanced dataset. The indicators are highly correlated, with correlation coefficients above 0.8, see Supplementary Appendix (Table SA3). The baseline estimations this study therefore uses Government Effectiveness (GovEff) as a representative for the series of governance indicators.

Finally, trade openness (Trade) is measured as the total level of imports and exports of goods and services measured as a percentage of GDP [51]. The total level of Foreign Direct Investment (FDI) is measured as a percentage of GDP [52]. A summary of descriptive statistics for each variable discussed can be seen below in Table 2. A time trend (Time) is also included given by a series of dummy variables representing each year to remove any potential linear trend caused by the timeline.

4. Results

In this section, we first present the tests for spatial dependence in the dependent variable (oxygen content). Secondly, the non-spatial panel OLS model given in Equation (1) was used as discussed in Section 3 to conduct tests for econometric method selection. Finally, this is followed by an estimation and analysis of results obtained using the Spatial Lag Model (SLM) given in Equation (4).

4.1. Baseline tests for spatial dependence

The results of the Moran's I and Geary's C tests using the constructed the spatial weight matrices for $k = 1, \ldots, 6$ nearest neighbours, are seen below in Table 3. The results show that for each weight matrix, results are significant at the 1% statistical level with a positive value from Moran's I test. These results are also backed up from the results for Geary's C test. This indicates that positive spatial autocorrelation is observed between the European countries within the dependent variable which confirms that we may continue to test which spatial econometric method is appropriate.

4.2. Spatial econometric method selection

From the results given below in Table 4, we can see that the Global Moran's I test on the regression residuals in each OLS model specification is significant at the 1% statistical level across the different spatial weight matrices, an indication of the presence of spatial spillovers. The classical LM tests for the spatial error and spatial lag models also show statistical significance for $k = 2$ to 6 nearest neighbours. However, from results of the robust LM (RLM) tests, we see that the results for the spatial error show no statistical significance. The tests for the spatial lag model reveal statistical significance at the 5% level for $k = 2$ to 6 nearest neighbours. From these results, we may deduce that from the presence of significant spatial dependence in the data, it would be inappropriate for the EKC model to be estimated via OLS as this may yield biased and inconsistent estimates and that it may be best to estimate a spatial lag model. Previous literature also contends that possible omitted variable bias affects spatial regression models less than that for OLS regression where such effects and spatial dependence are in the spatial lag term, for the case of the spatial lag model (SLM) [53,54].

4.3. Pooled OLS regression

The results of the pooled OLS model is shown in column (1) of Table 5. We see that the values for real GDP per capita are statistically significant at the 1% level throughout. These results indicate the existence of the EKC, showing the expected result of an inverse N-shape, between oxygen content and real GDP per capita. Results also show that livestock density and government effectiveness are statistically significant at the 1% level. Here, results suggest that increases in government effectiveness are associated with higher levels in oxygen content whilst increases in livestock density are associated with decreasing levels in oxygen content. However, given the tests for spatial autocorrelation given in section 4.2, the existence of spatial spillovers is seen within the model which indicate that the non-spatial OLS estimates may be severely biased and inconsistent. Thus, we continue to estimate the panel spatial lag model via maximum likelihood.

4.4. Spatial regressions

Given equation (4), we present the results as shown below in Table 5 of the maximum likelihood estimations of the spatial lag model using fixed effects (see columns 2–6). Firstly, we see that lambda, which denotes the spatial autocorrelation coefficients, is significant at the 1% level with a positive value. This indicates that there exist significant spatial spillovers within the model. Overall, we may see that the total effect of our independent variables may not only have direct consequences within a given country's own water quality but also through indirect consequences on other countries through spatial spillovers.

The estimates from the SLM model cannot be interpreted as partial derivatives in the typical regression model fashion [55]. In order to obtain the correct signs and magnitudes of the coefficients, it is necessary to conduct an impact analysis as outlined by LeSage and Pace [44] where we also obtain the direct, indirect and total impacts which detail the effects from home, from neighbours and the total

Table 2
Descriptive statistics.

Variable	Description	Mean	Std. dev.	Min	Max	*N*
O^2	Median value of oxygen content (mg/l)	3.97	3.37	0.25	32	340
GDP	Real GDP per capita (USD, 2010 value)	27 481	15 836	4700	84 400	340
PopDens	Total population density (km^2)	142.12	114.68	16.92	500.59	340
LiveDens	Livestock density (livestock units per km^2)	40.45	37.80	2.78	159.60	340
Voice	Worldwide governance indicator – Voice and accountability	1.24	0.26	0.70	1.80	340
GovEff	Worldwide governance indicator – Government effectiveness	1.37	0.56	0.15	2.35	340
RegQ	Worldwide governance indicator – Regulatory quality	1.36	0.36	0.51	2.10	340
Corr	Worldwide governance indicator – Control of corruption	1.31	0.75	−0.07	2.47	340
Trade	Trade openness – imports and exports of goods and services (% of GDP)	109.48	58.19	44.73	382.29	340
FDI	Foreign direct investment, net inflows (% of GDP)	8.32	20.63	−58.32	252.31	340

Note: *N* refers to the number of observations.

Table 3
Global spatial autocorrelation tests for Oxy.

Test stat.	*k* nearest neighbours					
	$k = 1$	$k = 2$	$k = 3$	$k = 4$	$k = 5$	$k = 6$
Moran's *I*-stat	0.228***	0.277***	0.284***	0.306***	0.318***	0.315***
Geary's *C*-stat	0.753**	0.856	0.771***	0.726***	0.708***	0.723***

Note: $*p < 0.1$; $**p < 0.05$; $***p < 0.01$.

Table 4
Tests for spatial econometric method selection.

	k nearest neighbours					
	$k = 1$	$k = 2$	$k = 3$	$k = 4$	$k = 5$	$k = 6$
Global Moran's *I*	0.09	0.09**	0.11***	0.14***	0.16***	0.15***
LM-test: no spatial error	1.73	3.37*	8.31***	16.18***	25.19***	27.60***
LM test: no spatial lag	2.21	6.33**	12.94***	22.21***	31.63***	33.54***
RLM-test: no spatial error	0.03	1.47	0.83	0.25	0.00	0.11
RLM test: no spatial lag	0.51	4.43**	5.47**	6.28**	6.44**	6.06**

Note: $*p < 0.1$; $**p < 0.05$; $***p < 0.01$.

impact, respectively. These results are shown below in Table 6.

Considering the total impacts, results show that GDP per capita (including the squared and cubic values) are consistently significant at the 1% level. This displays an EKC relationship with the expected signs and inverted *N*-shape. Results also show that livestock density (LiveDens) is significant at the 1% level throughout. Government effectiveness (GovEff) is also significant at the 1% and 5% level for $k = 1$ and $k = 2\ldots6$ neighbours, respectively. Trade (lnTrade) is also significant at the 10% level for $k = 4\ldots6$ neighbours. Finally, significance is observed at the 10% level for the time trend (Time; results not shown) for $k = 4\ldots6$ neighbours. For the results of lnTrade and Time, as these results are not consistent throughout, this implies a less than robust outcome.

The results imply that with a positive sign for GovEff and lnTrade, countries with a higher level of government effectiveness and trade openness are associated with higher oxygen content levels. With a negative sign observed for LiveDens, this suggests that an increase in livestock density is associated with lower oxygen content levels. An interesting observation is that the indirect impacts (neighborhood effects) are consistently lower in magnitude than the direct impacts apart from when six neighbours are considered. This implies that the impacts domestically are higher than those from neighbouring countries.

Comparing these results to that from the OLS estimation, it appears that the coefficient estimates from the latter, assuming independent observations, may display substantial bias. We see this as results for Trade and the time trend were not significant in the OLS regression but are significant within the spatial model. However, neither the spatial nor the OLS models show statistical significance for population density and FDI.

Following the approach by Plassman and Khanna (2007) for calculating the turning points from a cubic function, using the total impacts, we obtain the point to which oxygen content begins to improve and the point to which oxygen content begins to worsen again given the level of real GDP per capita. The results show that the first turning point is within the range of 22,749 and 27,246 USD. We find that the second turning point to which oxygen content begins to fall is within the range of 35,686 and 40,311 USD. As shown in

Table 5
Results of spatial lag model and pooled OLS.

		k nearest neighbours				
Variable	OLS	$k = 2$	$k = 3$	$k = 4$	$k = 5$	$k = 6$
lnGDP	−64.62*** (14.87)	−70.98*** (13.91)	−70.63*** (13.69)	−72.96*** (13.16)	−75.48*** (13.02)	−76.96*** (12.86)
$(\text{lnGDP})^2$	20.694*** (5.10)	22.97*** (4.77)	22.88*** (4.70)	23.73*** (4.52)	24.64*** (4.47)	25.24*** (4.42)
$(\text{lnGDP})^3$	−2.18*** (0.57)	−2.43*** (0.53)	−2.42*** (0.52)	−2.52*** (0.50)	−2.62*** (0.50)	−2.70*** (0.49)
lnPopDens	−0.16 (0.34)	−0.21 (0.32)	−0.25 (0.31)	−0.24 (0.30)	−0.18 (0.30)	−0.23 (0.30)
LiveDens	−0.03*** (0.01)	−0.03*** (0.01)	−0.03*** (0.01)	−0.03*** (0.01)	−0.03*** (0.01)	−0.02*** (0.01)
GovEff	1.86*** (0.62)	1.61*** (0.57)	1.45** (0.56)	1.30** (0.54)	1.32** (0.54)	1.24** (0.53)
lnTrade	0.79 (0.59)	0.75 (0.55)	0.80 (0.54)	0.79 (0.52)	0.88* (0.52)	0.88* (0.51)
FDI	0.002 (0.008)	0.003 (0.01)	0.002 (0.01)	0.002 (0.01)	−0.000 (0.001)	−0.000 (0.001)
Constant	66.17*** (12.24)					
Spatial (λ)		0.27*** (0.05)	0.34*** (0.05)	0.45*** (0.05)	0.48*** (0.05)	0.53*** (0.05)
N	340	340	340	340	340	340
Cross-sections	20	20	20	20	20	20
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Time trend	Yes	Yes	Yes	Yes	Yes	Yes

Note: $^*p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$; *p*-values given in parentheses.

Table 2, we see that the current average real GDP per capita (27,481 USD) is just greater than the initial turning point range but less than the second turning point calculated. This would suggest that on average, the current economic development within Europe is associated with increases in oxygen content, hence improved water quality.

Considering individual countries (Table A1 in the appendix), we take the average real GDP per capita values, given in thousands of USD, across two periods: Period 1 (1998–2005) and Period 2 (2006–2014). From these results, we see that most countries considered fall between each turning point range. However, the Czech Republic, Estonia, Latvia, Lithuania, Poland and Slovakia are below the first turning point across both periods, indicating that economic development can imply a decrease in water quality.[6] Also, Denmark and Luxembourg have average real GDP per capita rates that are above the second turning point in both periods which indicate that their economic development in the two periods has been high enough to be associated with declines in water quality. We also see from the results that Cyprus and Spain in Period 1 has an average GDP rate below the first turning point but a value in Period 2 within the turning point ranges. This indicates that their economic development has improved across time to be consistent with a change from decreases to increases in oxygen content.

4.5. Robustness checks

For robustness, two other estimations were conducted with the first including only real GDP per capita as a predictor of water oxygen content. The second estimation includes also the variables for population and livestock density (PopDens and LiveDens). For these, results were consistent with the values given in the estimation provided in Table 5 with very similar levels in the spatial autoregressive coefficient as well. The results are not shown here for reasons of brevity and space.

We also tested the result of including all governance indicator variables instead of one representative variable as done in the main results section. The results for the income variable are seen in the Appendix (Table A2), and the full results can be found in the Supplementary Appendix (Table SA4). We observe that the results are largely the same, at the expected sign, and with similar impacts from GDP per capita, livestock density and trade openness.[7] From the results of the governance indicators we see statistical significance with a positive value for government effectiveness, GovEff, as well as voice and accountability, Voice. Significance is also observed for regulatory quality, but with a negative coefficient. However, due to the level of correlation between these variables, including all five together produces a result that would be heavily biased and may produce inconsistent outcomes.

We also tested alternate specifications of the spatial weighting matrix considering other spatial relationships than the number of nearest neighbours. First, we considered the distance between centroids within the spatial matrix, i.e. 200 km, 400 km, etc. Doing this, we find that the results were very similar to the results given above and did not change conclusions. For the sake of brevity, the results are not shown here.

In the case of water quality, the physical spillovers of pollutants between different spatial units can be expected to depend on whether they are located upstream or downstream, and whether they share common water bodies such as international rivers. To

[6] In this context it can be relevant to note that one could intuitively expect that water quality would be lower in the East European countries, for example because of the history of large overuse of fertilizers in the agricultural sector during the Soviet era until the 1990. In spite of such expectations, upwards trends in nutrient concentrations were found after the Soviet era when using in long term monitoring data in Estonia and Latvia [56], an observation which is consistent with our results. The East European countries were further required to undertake substantial changes in their economic and environmental policy institutions as part of the conditions for joining the EU in 2007. The historical and institutional differences between the East European countries and other countries are captured in our analysis through the governance indicators and the country fixed effects.

[7] Only GDP results are shown to conserve space. For full results, see Table SA4 in the Supplementary Appendix.

Table 6
Impact analysis of spatial lag model results.

Variable	*k* nearest neighbours				
	$k = 2$	$k = 3$	$k = 4$	$k = 5$	$k = 6$
lnGDP					
Direct	−72.61*** (−5.08)	−72.67*** (−5.13)	−76.46*** (−5.51)	−79.51*** (−5.76)	−81.35*** (−5.95)
Indirect	−24.23*** (−3.33)	−34.21*** (−3.38)	−55.25*** (−3.72)	−65.46*** (−3.77)	−82.23*** (−3.82)
Total	−96.84*** (−4.87)	−100.69*** (−4.81)	−131.71*** (−4.62)	−144.97*** (−5.06)	−163.58*** (−5.05)
$(\text{lnGDP})^2$					
Direct	23.50*** (4.79)	23.54*** (4.85)	24.87*** (5.24)	25.96*** (5.50)	26.68*** (5.70)
Indirect	7.84*** (3.25)	11.08*** (3.30)	17.97*** (3.64)	21.37*** (3.70)	26.96*** (3.75)
Total	31.34*** (4.63)	34.62*** (4.59)	42.84*** (4.78)	47.32*** (4.89)	53.64*** (4.90)
$(\text{lnGDP})^3$					
Direct	−2.49*** (−4.60)	−2.49*** (−4.65)	−2.64*** (−5.03)	−2.76*** (−5.30)	−2.85*** (−5.52)
Indirect	−0.83*** (−3.18)	−1.17*** (−3.24)	−1.91*** (−3.57)	−2.27*** (−3.64)	−2.88*** (−3.70)
Total	−3.32*** (−4.46)	−3.66*** (−4.42)	−4.54*** (−4.62)	−5.04*** (−4.75)	−5.73*** (−4.79)
lnPopDens					
Direct	−0.22 (−0.65)	−0.25 (−0.75)	−0.26 (−0.77)	−0.19 (−0.58)	−0.25 (−0.75)
Indirect	−0.07 (−0.63)	−0.12 (−0.72)	−0.19 (−0.75)	−0.16 (−0.57)	−0.25 (−0.73)
Total	−0.30 (−0.65)	−0.37 (−0.75)	−4.42 (−0.77)	−0.35 (−0.58)	−0.50 (−0.75)
LiveDens					
Direct	−0.03*** (3.53)	−0.03*** (−3.42)	−0.03*** (−3.27)	−0.03*** (−3.26)	−0.03*** (−3.08)
Indirect	−0.01*** (−2.75)	−0.01*** (−2.72)	−0.02*** (−2.74)	−0.02*** (−2.73)	−0.03*** (−2.62)
Total	−0.04*** (−3.46)	−0.04*** (−3.32)	−0.05*** (−3.15)	−0.05*** (−3.12)	−0.05*** (−2.93)
GovEff					
Direct	1.65*** (2.85)	1.49*** (2.60)	1.37** (2.44)	1.39** (2.50)	1.32** (2.39)
Indirect	0.55** (2.35)	0.70** (2.22)	0.99** (2.17)	1.15** (2.21)	1.33** (2.12)
Total	2.20*** (2.80)	2.19** (2.55)	2.35** (2.38)	2.54** (2.42)	2.64** (2.30)
lnTrade					
Direct	0.77 (1.39)	0.83 (1.52)	0.83* (1.56)	0.92* (1.74)	0.93* (1.77)
Indirect	0.26 (1.30)	0.39 (1.41)	0.60 (1.46)	0.76 (1.62)	0.95* (1.65)
Total	1.02 (1.39)	1.22 (1.50)	1.43* (1.54)	1.68* (1.71)	1.88* (1.74)
FDI					
Direct	0.003 (0.38)	0.002 (0.21)	0.003 (0.37)	−0.000 (−0.03)	−0.000 (−0.03)
Indirect	0.001 (0.36)	0.001 (0.20)	0.002 (0.35)	−0.000 (−0.04)	−0.000 (−0.04)
Total	0.004 (0.38)	0.003 (0.21)	0.005 (0.36)	−0.000 (−0.03)	−0.000 (−0.04)
	Income Turning Point (TP; in USD)				
TP#1	27,246	22,749	26,731	26,751	26,503
TP#2	35,686	40,311	36,176	35,842	35,905

Note: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$; z-values given in parentheses.

account for the role of such physical spillovers in water quality, we proceeded as follows. First, we constructed different spatial weight matrices to capture this physical relationship as closely as possible. For this purpose, we used geospatial information (maps) from the Water Information System for Europe (WISE) of the WFD reference database for 2016 (the latest available version). This data is reported to the European Commission under the WFD reporting requirement on member countries. We then combined geodata on river basin districts and surface water body shapefiles to determine countries that share a common water body. A river basin district covers an area of land (and sea) consisting of one or more neighbouring river basins, along with associated coastal waters. Surface water body geo-information on the other hand is defined as a body of surface water with significant element of water surface like a lake, river, stream or a transnational waterbody or coastal water.[8]

Based on the above information, we first constructed a symmetric spatial weight matrix where $w_{ij} = 1$ if two or more countries share a common waterbody and $w_{ij} = 0$ otherwise. We do not distinguish between upstream and downstream countries in this specification. We call this matrix a symmetric–contiguous spatial weight matrix (see Refs. [57,58].

A second matrix is created by also accounting for the physical elevation of each country. Average elevation values are compared between neighbour(s) who share a common waterbody to determine upstream versus downstream states. A country with a higher elevation value to its neighbour(s) with a shared waterbody is considered to be an upstream candidate with its river potentially flowing downstream to its neighbour(s). In this case, the weight for an upstream state is assigned the value $w_{ij} = 1$ as a neighbour to the

[8] https://www.eea.europa.eu/data-and-maps/data/wise-wfd-protected-areas-1.

downstream states. The reverse cannot hold for the downstream state(s) in relation to its upstream neighbour(s), for which $w_{ij} = 0$, thus resulting in an asymmetric contiguous spatial weight matrix. For example, given the elevation of Austria (910 m) compared to the Czech Republic (91 m) and Germany (263 m) who are contiguous in relation to a shared waterbody, we assume Austria to be an upstream neighbour to Czech Republic and Germany. Similarly, Germany is assumed to be an upstream neighbour to Netherlands (30 m) and Denmark (34 m). While this approach is arguably a simplification, it does to some degree account for the transboundary nature of water pollution considered in this study.[9] For the two constructed weight matrices, we row standardize them following standard practice in applied spatial econometrics literature.

The third and final weight matrix developed to reflect physical spillovers uses the preceding asymmetric matrix, but in this case, we assign a bigger weight to the impact of upstream countries on their downstream neighbour(s) (1) compared to that of downstream countries on their upstream neighbour(s) (0.5). The intuition is that the downstream neighbours are more exposed to the negative water pollution externality from upstream neighbours than the opposite [57]. Although the process of assigning the weight is *ad hoc*, following Takahashi et al. [57], this approach reflects the possibility of mutual physical impacts also in the case where an upstream – downstream relationship could be expected to dominate. All three weight matrixes for physical spillovers can be found in Table SA4 in the Supplementary Appendix.

Using the three different constructed spatial weight matrices above, we re-estimated the baseline SAR model as another check of sensitivity of the results. The results for both the first stage estimates and associated marginal impacts for income are shown in Table A3 in the Appendix. Overall, the results are comparable to those from the SLM model. Evidently, we still observe a significant inverted *N*-shaped EKC relationship as in the baseline. This observation is robust even if we control for all the governance indicators (Table A4 in the Appendix). The only noticeable difference between these results and the baseline estimates lie with the spatial interaction parameter (λ) which changes direction to negative.

Furthermore, we compare the baseline results with those from alternative spatial panel models such as the spatial error model (SEM), spatial autoregressive model with autocorrelated errors (SAC) and the spatial Durbin model (SDM). The SDM allowed us to properly account for spatial interaction in the governance indicators by including additional spatially weighted covariates to capture potential spillovers of these indicators on neighbouring states' water quality. In all these models, we utilize the same three spatial weight matrices reflecting physical spillovers, constructed for the preceding robustness check. Most important, our conclusion regarding the EKC relation still holds irrespective of the model (see Table SA6 and SA7 in the Supplementary Appendix). The results further imply that improved government effectiveness, GovEff, in a neighbouring country is significantly associated with higher water oxygen content levels in the domestic country (column 8 in Table SA5 supplementary appendix). However, when we incorporate all the government indices in the respective SDM models, the evidence is less satisfactory but the EKC results still hold. In that case, we find that only that the rule of law (Law) and regulatory quality (Reg) in neighbouring states improves water quality in own jurisdiction.[10] Baseline results are finally compared with the case where none of the variables are log-transformed. While the results on the EKC curvature are qualitatively consistent with the baseline findings, the magnitudes are less informative in terms of interpretation (Table SA8 in Supplementary Appendix). The near zero coefficient estimates especially of the income variables might be due to scaling problems. This makes the log-transformed specification more preferable, which is a feature extant in the EKC literature.

5. Discussion and conclusions

The purpose of this study was to estimate the relationship between real GDP per capita and water quality, proxied by oxygen content levels, within Europe using a spatial panel approach with a cubic function for national income. Furthermore, this study also addresses criticisms of the traditional EKC approaches through use of a cubic function and addition of institutional quality and market openness variables.

Results show a strong significant relationship between oxygen content and income with the expected inverted *N*-shape which shows an EKC relationship. From estimated turning points of 22,749 to 27,246 USD for the initial turning point and 35,686 to 40,311 USD for the second turning point. Furthermore, our initial turning point range is similar of that by Gassebner et al. [8], (26,800 USD), while it is below that given by Lee et al. [5] (38,220 USD). Both our estimated turning points are considerably less than those estimated by Farzin and Grogan [9]. The two former study BOD levels, which are related to oxygen contents, whereas the latter considered ammonia and fecal coliform bacteria, which can explain the difference in results.

We can then gather that the current average real GDP per capita within Europe falls within the bounds estimated in this paper. Therefore, one would be inclined to assume that on average, economic development within Europe should be expected to lead to improved water quality. However, our results also show that this may not necessarily be the case. The reason is that a considerable number of countries have either a too low or too high income per capita to be in the range where economic development is associated water quality improvements. This observation tends to support results in Torras and Boyce (1998) and Rupasingha et al. [16]

[9] For example, this weight matrix does not take into account the location of watershed boundaries within a country, which affect the water flows from one country to another. However, it should be noted that the physical impact of one country on water quality in another cannot be determined only by taking the size of common watersheds into account. Another factors that also matters as the size of runoff and water flows: to our knowledge there is no data on the magnitude of the actual transports of water pollutants between countries across Europe. Moreover, there are many cases where the upstream and downstream relationships between countries is unclear, including for example lakes and rivers located on the border between two countries, and coastal areas in the neighborhood of a country border.

[10] Results are available on request.

suggesting that income inequality is associated with a worsening of water quality. Torras and Boyce (1998) argue that this could be motivated by a more equitable distribution of power contributing positively to environmental quality, by enhancing the influence on policy of those who bear the costs of pollution, relative to the influence of those who benefit from pollution-generating activities. However, this explanation would not apply in our case, where we have inequality between countries rather than within the same jurisdiction. Instead our results offer a different explanation for the negative relationship between income inequality and water quality, namely the existence of an inverted N-shaped EKC. This raises a concern regarding how EU countries that fall outside the ranges of sustainable economic development can achieve their water quality targets.

Secondly, spatial autocorrelation is significant throughout our analysis displaying that spatial spillovers, related to environmental and institutional factors, between countries are an important feature in EKC analysis. Thus, inclusion of spatial effects in the analysis is necessary to avoid biased estimates. This is consistent with previous literature emphasizing the importance for such analysis [20,21] as well as empirical analysis considering the linkage between explanatory variables and water quality [9]. Significance of spatial spillovers did not decrease when considering additional nearest neighbours, contradicting findings from Ref. [59] that spillovers are constrained by national borders with immediate neighbours. Furthermore, with direct effects being consistently of a larger magnitude than indirect effects within the impact analyses, this would infer to us that the domestic effects are larger than that from neighbouring countries. Whereas our baseline estimations, which account for the general spatial impact of the nearest neighbours, show significant and positive spatial spillovers, the spatial spillovers are significant and negative when using different spatial matrices specifically reflecting shared water bodies and the upstream-downstream nature of the physical pollutant spillovers. Although our conclusions on the impact of our explanatory variables are robust to the choice of spatial matrix, this implies that we cannot draw any strong conclusions on the nature and drivers of the spatial effects. Negative spatial interactions are sometimes interpreted as being a consequence of strategic environmental policymaking, where countries could choose to apply lax regulation in order to attract investments [60]; Fredriksson and Millimet 2003 [61]; Millimet and Roy 2010). However, it is not evident that such an interpretation is relevant in this case, given the positive spatial interaction in the baseline model. Instead, the negative spatial effects when using the physical spillover matrices could potentially be due to the limited number of non-zero values in the spatial weight matrices, ultimately explained by the exclusion of several countries due to lack of data for the dependent variable. Another potential explanation could be that economic activities impacting water quality are non-uniformly distributed within countries. For example, an upstream country could have high water quality in large parts of its territory, but polluting activity could be located close to the border to downstream countries, which might generate the observed outcome. Hence, future research including additional countries would be valuable to further examine the magnitude of physical spillover effects. However, the baseline model allows us to capture both physical, economic and institutional spillovers, and indicates that the sum of those together exert a positive spillover effect between countries.

The results show that increased livestock density is associated with lower levels of water quality, this fits in with findings by, e.g., Ephraim et al. [62] and Wen et al. [19]. Although higher livestock density could be associated by 'pointification' of nonpoint emissions, allowing for more efficient nutrient mitigation techniques, this is not sufficient to offset the negative impact of livestock on water quality. Results show that increased population density has no significance which contradicts findings in the literature [7,27,28,63].

Our results on the representative indicator for the five governance indicators, government effectiveness, was significant with a positive sign. This stands in line to assertions by previous literature sources [18,23]. Neef [64] and Brown [34] criticizes analysis using national governance indices where such variables ignore the differences between national and local governance. This is argued to be problematic as national policy may either not reflect resistance from local communities, asymmetry of knowledge or may understate potential benefits of devolved decision making. Future studies may look to assess the relative importance of local and national governance, given the importance of local decisions for water quality [29,65]. Our results also show that openness to trade has a significant effect in the positive direction. This result fits in with findings by Aklin [36] and Fang et al. (2018) as well as previous literature on water quality in the EKC context [7,8]. Together, these results suggest that strengthening of governance and increased economic openness could potentially help remediating water quality problems.

A limitation of this study is the limited time dimension of the dataset, which precludes analysis of the impact of common EU policies specifically targeting water pollution, such as the Nitrate and Wastewater Directives, on water quality within the Union. Furthermore, missing data was an issue, with certain European countries having little to no data available. As data becomes more readily available, future studies may exploit this topic.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wre.2021.100182.

Author statement

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Table A1
Individual average country income in 1998–2005 (Period 1) and 2006–2014 (Period 2).

Country	GDP (tUSD) Period 1	Below	Within	Above	GDP (tUSD) Period 2	Below	Within	Above
Austria	32.0		X		35.8		X	
Belgium	30.6		X		33.6		X	
Cyprus	21.3	X			22.8		X	
Czech Republic	11.8	X			15.0	X		
Denmark	42.3			X	44.7			X
Estonia	8.6	X			12.3	X		
Finland	31.3		X		35.3		X	
France	29.3		X		31.1		X	
Germany	29.0		X		32.5		X	
Ireland	33.9		X		38.5		X	
Italy	27.5		X		26.9		X	
Latvia	6.1	X			9.5	X		
Lithuania	6.1	X			9.8	X		
Luxembourg	71.0			X	79.6			X
Netherlands	34.8		X		38.2		X	
Poland	6.7	X			9.4	X		
Slovakia	8.5	X			12.5	X		
Spain	21.9	X			23.2		X	
Sweden	34.5		X		39.6		X	
United Kingdom	27.7		X		30.1		X	

Note: X indicates whether income is below, within, or above the two turning points in the respective period.

Table A2
Impact analysis on the spatial lag estimates with all institutional quality variables included.

Variable	*k* nearest neighbours				
	$k = 2$	$k = 3$	$k = 4$	$k = 5$	$k = 6$
lnGDP					
Direct	−68.55*** (−4.84)	−68.48*** (−4.87)	−72.03*** (−5.22)	−75.13*** (−5.46)	−76.86*** (−5.63)
Indirect	−17.82*** (−2.92)	−25.01*** (−3.00)	−42.74*** (−3.40)	−51.02*** (−3.46)	−64.06*** (−3.51)
Total	−86.37*** (−4.64)	−93.49*** (−4.56)	−114.76*** (−4.71)	−126.15*** (−4.81)	−140.92*** (−4.80)
$(\ln GDP)^2$					
Direct	22.33*** (4.60)	22.32*** (4.63)	23.53*** (4.97)	24.60*** (5.22)	25.28*** (5.41)
Indirect	5.81*** (2.86)	8.15*** (2.94)	13.96*** (3.32)	16.71*** (3.39)	21.07*** (3.46)
Total	28.13*** (4.42)	30.47*** (4.36)	37.50*** (4.53)	41.31*** (4.64)	46.35*** (4.66)
$(\ln GDP)^3$					
Direct	−2.39*** (−4.47)	−2.39*** (−4.49)	−2.52*** (−4.82)	−2.64*** (−5.08)	−2.72*** (−5.30)
Indirect	−0.62*** (−2.83)	−0.87*** (−2.90)	−1.50*** (−3.27)	−1.79*** (−3.35)	−2.27*** (−3.42)
Total	−3.02*** (−4.31)	−3.26*** (−4.25)	−4.02*** (−4.41)	−4.43*** (−4.54)	−4.99*** (−4.58)
	Income Turning Point (TP; in USD)				
TP#1	27,777	27,317	27,184	26,963	26,804
TP#2	34,320	34,993	35,005	35,204	35,120

Note: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$; z-values given in parentheses. Results extracted from Table SA4 in supplementary appendix. See Table SA4 for the full results, including all other covariates.

Table A3
Results of SAR model using three different constructs of spatial weight matrix.

Variable	(1)	(2)	(3)
lnGDP	−85.90*** (19.78)	−84.04*** (19.78)	−84.57*** (19.75)
$(\ln GDP)^2$	27.89*** (7.41)	27.34*** (7.42)	27.36*** (7.41)
$(\ln GDP)^3$	−3.00*** (0.87)	−2.96*** (0.87)	−2.94*** (0.87)
lnPopDens	−0.40 (1.45)	−0.33 (1.45)	−0.41 (1.45)
LiveDens	−0.02 (0.04)	−0.01 (0.04)	−0.02 (0.04)

(*continued on next page*)

Table A3 (*continued*)

Variable	(1)	(2)	(3)
GovEff	1.20 (0.87)	0.88 (0.86)	1.15 (0.87)
lnTrade	2.53* (1.42)	2.78* (1.43)	2.74* (1.43)
FDI	0.003 (0.006)	0.002 (0.006)	0.003 (0.006)
Spatial (λ)	−0.11** (0.048)	−0.14** (0.057)	−0.10** (0.042)
N	340	340	340
Cross-sections	20	20	20
Country FE	Yes	Yes	Yes
Time trend	Yes	Yes	Yes
	Marginal impact analysis		
		Direct effect	
lnGDP	−85.70*** (20.42)	−83.38*** (20.32)	−84.31*** (20.37)
(lnGDP)^2	27.76*** (7.66)	27.06*** (7.63)	27.21*** (7.65)
(lnGDP)^3	−2.98*** (0.90)	−2.92*** (0.90)	−2.91*** (0.90)
		Indirect effect	
lnGDP	7.59** (3.83)	5.84** (2.72)	7.13** (3.40)
(lnGDP)^2	−2.45* (1.27)	−1.89** (0.92)	−2.29** (1.13)
(lnGDP)^3	0.26* (0.14)	0.20** (0.10)	0.25** (0.12)
		Total effect	
lnGDP	−78.10*** (18.99)	−77.54*** (19.24)	−77.18*** (19.05)
(lnGDP)^2	25.31*** (7.13)	25.17*** (7.22)	24.92*** (7.15)
(lnGDP)^3	−2.72*** (0.84)	−2.71*** (0.85)	−2.67*** (0.84)
	Income Turning Point (TP; in USD)		
TP #1	21,050	21,352	20,623
TP #2	24,778	24,172	23,718

Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Estimates for each spatial model (3 columns) corresponds to results based on three different spatial weights matrices: column (1) has a symmetric matrix accounting for effects between countries with a contiguous water body; column (2) has an asymmetric matrix depicting potential upstream and downstream relation based on having a common water body; column (3) has a matrix similar to that in column (2) but with different weights for upstream-downstream countries, following [57,58]. We show only the coefficients of interest and relevant for the EKC test, GDP. The other coefficient results are available on request.

Table A4
SAR results using three different spatial weight matrices with all governance indicators.

Variable	(1)	(2)	(3)
lnGDP	−92.85*** (19.82)	−90.82*** (19.85)	−91.40*** (19.81)
(lnGDP)^2	30.40*** (7.44)	29.86*** (7.46)	29.85*** (7.44)
(lnGDP)^3	−3.28*** (0.87)	−3.24*** (0.88)	−3.22*** (0.87)
lnPopDens	−0.72 (1.46)	−0.71 (1.46)	−0.74 (1.46)
LiveDens	−0.02 (0.04)	−0.01 (0.04)	−0.02 (0.04)
Voice	−3.25* (1.78)	−3.19* (1.78)	−3.24* (1.78)
GovEff	1.35 (0.98)	1.19 (0.98)	1.33 (0.98)
Reg	−0.20 (1.08)	−0.19 (1.08)	−0.18 (1.08)
Corr	2.10* (1.08)	1.91* (1.09)	2.02* (1.08)
Law	−0.96 (1.66)	−1.31 (1.65)	−1.02 (1.65)
lnTrade	2.47* (1.42)	2.62* (1.43)	2.64* (1.43)
FDI	0.001 (0.006)	0.001 (0.006)	0.001 (0.006)
Spatial (λ)	−0.11** (0.05)	−0.13** (0.06)	−0.10** (0.04)
Observations	340	340	340
Cross-sections	20	20	20
Country FE	Yes	Yes	Yes
Time trend	Yes	Yes	Yes
	Marginal impact analysis		
		Direct effect	
lnGDP	−92.71*** (20.54)	−90.15*** (20.40)	−91.17*** (20.48)
(lnGDP)^2	30.29*** (7.71)	29.58*** (7.67)	29.71*** (7.70)
(lnGDP)^3	−3.26*** (0.90)	−3.20*** (0.90)	−3.19*** (0.90)
		Indirect effect	
lnGDP	8.29* (4.52)	5.82* (3.08)	7.52* (3.95)
(lnGDP)^2	−2.70* (1.51)	−1.90* (1.04)	−2.44* (1.32)
(lnGDP)^3	0.29* (0.17)	0.21* (0.12)	0.26* (0.15)
		Total effect	
lnGDP	−84.42*** (18.68)	−84.34*** (19.19)	−83.65*** (18.86)
(lnGDP)^2	27.59*** (7.05)	27.67*** (7.23)	27.26*** (7.12)
(lnGDP)^3	−2.97***	−2.99***	−2.93***

(*continued on next page*)

Table A4 (*continued*)

Variable	(1)	(2)	(3)
	(0.83)	(0.85)	(0.84)
	Income Turning Point (TP; in USD)		
TP #1	24,241	24,571	23,840
TP #2	30,350	30,584	29,389

Notes: Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Estimates for each spatial model (3 columns) corresponds to results based on three different spatial weights matrices: column (1) has a symmetric matrix accounting for effects between countries with a contiguous water body; column (2) has an asymmetric matrix depicting potential upstream and downstream relation based on having a common water body; column (3) has a matrix similar to that in column (2) but with different weights for upstream-downstream countries, following [57,58]. We show only the coefficients of interest and relevant for the EKC test, GDP. The other coefficient results are available on request.

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