DATA-DRIVEN MODELLING AND APPLICATION IN CIRCULAR ECONOMY: A EUROPEAN WATER EFFICIENCY STUDY

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by

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$\boldsymbol{c}_{\bullet j}^{(t,t+1)}$	DMU$_j$'s carryover for division $\bullet$ from period t to period $t+1$
δ	Divisional efficiency
D_W	Shephard water distance function
DNP	Dynamic network production technology
K	Capital stock
L	Labour force
λ_{jk}^{t}	Intensity of country j corresponding to division k at period t (indicating the importance of DMU j in measuring the efficiency score of DMU o)
$\lambda_{j}^{\bullet,t}$	Intensity assigned to DMU$_j$ (as against peers) in relation to division $\bullet$ at period t
NP	Network production technology
P	Production technology
Q	Water quality
ρ	Period-divisional efficiency
s_{iok}^{t-}	Slack of input resource i, country j, activity k, period t
$s_{\bullet k}^{t-}$	Slack of DMU$_k$'s given input for division $\bullet$ at period t
s_{dok}^{t+}	Slack of output product d, country j, activity k, period t
$s_{\bullet k}^{t+}$	Slack of DMU$_k$'s given output from division $\bullet$ at period t
$s_{\bullet k}^{t-/+}$	Input-type/output-type slack of DMU$_k$'s given link at period t
θ	Overall efficiency
τ	Period efficiency
TGR	Technology gap ratio
$\mathcal{v}_{jkc}^{(t,t+1)}$	Carryover, country j, activity k, period t to period $t+1$
W	Water

WE	Total-factor water efficiency
WI	Water input requirement set
x_{ijk}^{t}	Input resource i, country j, activity k, period t
$\boldsymbol{x}_{\bullet j}^{t}$	Input resource to DMU$_j$'s division $\bullet$ at period t
Y	Total output
y_{djk}^{t}	Output product d, country j, activity k, period t
$\boldsymbol{y}_{\bullet j}^{t}$	Output product from DMU$_j$'s division $\bullet$ at period t
$z_{j(k,h)_l}^{t}$	Link product, country j, activity k to activity h, period t
$\boldsymbol{z}_{\bullet j}^{t}$	DMU$_j$'s link from/to division $\bullet$ to/from downstream/upstream division at period t

LIST OF ABBREVIATIONS

AUT	Austria
BB	Brandenburg
BCC	Banker, Charnes and Cooper
BDEW	German Association of Energy and Water Industries
BEL	Belgium
BGR	Bulgaria
BIH	Bosnia-Herzegovina
BW	Baden-Württemberg
BY	Bavaria
CCR	Charnes, Cooper and Rhodes
CHE	Switzerland
CIP	Competitive industrial performance
COLS	Corrected ordinary least squares
CRS	Constant returns to scale
CYP	Cyprus
CZE	Czechia
DEA	Data envelopment analysis
DEU	Germany
DGP	Data generation process
DMC	Domestic material consumption
DMU	Decision-making unit
DNK	Denmark
EI	Energy Institute
EIA	Energy Information Administration
EIP	European Innovation Partnership
ESP	Spain
EST	Estonia
EU	European Union
EUR	Euro
FAO	Food and Agriculture Organization
FIN	Finland

FRA	France
GAMS	General Algebraic Modeling System
GBR	United Kingdom
GDP	Gross domestic product
GRC	Greece
GVA	Gross value added
HE	Hesse
HRV	Croatia
HUN	Hungary
IBNET	International Benchmarking Network
IRL	Ireland
ITA	Italy
KGOE	Kilogram of oil equivalent
LF	Latent factor
LR	Likelihood ratio
LTU	Lithuania
LUX	Luxembourg
LVA	Latvia
MHT	Medium- and high-technology
MLT	Malta
MV	Mecklenburg-Vorpommern
MVA	Manufacturing value added
NI	Lower Saxony
NLD	Netherlands
NOR	Norway
NW	North Rhine-Westphalia
OLS	Ordinary least squares
POL	Poland
PPS	Purchasing power standard
PRT	Portugal
ROU	Romania
RP	Rhineland-Palatinate
SBM	Slacks-based measure
SDG	Sustainable development goal

SFA	Stochastic frontier analysis
SFSO	Swiss Federal Statistical Office
SH	Schleswig-Holstein
SL	Saarland
SN	Saxony
SRB	Serbia
ST	Saxony-Anhalt
SVK	Slovakia
SVN	Slovenia
SWE	Sweden
TGR	Technology gap ratio
TH	Thuringia
UBA	Umweltbundesamt (German Environment Agency)
US	United States
UN	United Nations
UNIDO	UN Industrial Development Organization
VRS	Variable returns to scale
WDPA	World Database on Protected Areas
WFD	Water Framework Directive
WSSD	World Summit on Sustainable Development

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PEMODELAN BERPACUKAN DATA DAN APLIKASI DALAM EKONOMI KITARAN: KAJIAN KECEKAPAN AIR DI EROPAH

ABSTRAK

Pada tahun 2007, Kesatuan Eropah berikrar untuk menjadi komuniti yang cekap air, satu langkah penting ke arah pembangunan kelestarian. Namun, kemajuan terbatas akibat ketiadaan penanda aras yang relevan dan kekurangan pemahaman saintifik. Bagi menangani jurang ini, tesis ini memodelkan dan menilai kecekapan penggunaan air, sektor air awam, serta kitaran ekonomi air merentas negara-negara Eropah dengan mengintegrasikan kaedah matematik dan statistik, teori ekonomi, serta prinsip ekonomi kitaran. Sumber air Eropah semakin terancam akibat perubahan iklim, eksploitasi berlebihan, dan pencemaran. Walaupun usaha meningkatkan kecekapan penggunaan air dari segi permintaan dan penawaran penting untuk memperkukuh keselamatan air, kemajuan masih dihalang oleh kekurangan alat penilaian serta panduan berasaskan penyelidikan yang disesuaikan dengan kepelbagaian konteks. Meskipun terdapat usaha untuk mengamalkan prinsip ekonomi kitaran, masih terdapat potensi besar yang belum dimanfaatkan, khususnya dicontohi oleh Jerman. Sebagai respon, objektif tesis ini adalah untuk memperkenalkan kerangka penilaian penggunaan air dan kecekapan sektor air merentasi negara-negara Eropah, membekalkan pihak berkepentingan dengan alat sokongan keputusan dan pandangan berasaskan data bagi mengoptimumkan prestasi serta merintis pendekatan penilaian berasaskan kitar semula sumber secara menyeluruh bagi memperkukuh prestasi ekonomi air secara holistik. Tesis ini mengkaji kecekapan penggunaan air, termasuk faktor kontekstual, melalui analisis kluster dan model metafrontier parametrik faktor menyeluruh yang mempertimbangkan kualiti air, berdasarkan data panel negara

Eropah (2011-2020). Tesis ini juga menetapkan penanda aras kecekapan sektor air awam merentasi negara-negara Eropah melalui kaedah pemodelan rangkaian dinamik bukan parametrik, disertai dengan analisis statistik terhadap faktor-faktor luaran, berdasarkan data panel (2013-2020). Seterusnya, tesis ini memperkenalkan pendekatan penilaian kecekapan berbentuk kitaran bukan parametrik yang belum pernah diperkenalkan sebelum ini untuk penilaian prestasi komprehensif dan mengaplikasikannya bagi mengkaji ekonomi air Jerman di peringkat wilayah. Dapatan kajian menunjukkan kewujudan ketidakseimbangan kecekapan yang ketara di seluruh Eropah, dengan kemajuan teknologi menjadi pemacu peningkatan prestasi. Peningkatan kecekapan memerlukan penstrukturan semula sektor air yang disasarkan, seperti penaiktarafan infrastruktur, termasuk di Jerman. Tambahan pula, kawasan berorientasikan pemuliharaan yang cemerlang dalam kemampanan mungkin ketinggalan dalam kecekapan, memerlukan tumpuan terhadap perancangan guna tanah yang berhemat dan pemodenan yang serasi. Bagi membantu penggubal dasar dan pihak berkepentingan menangani cabaran air yang semakin meruncing di Eropah serta memastikan keselamatan air dan pembangunan mampan, tesis ini menyokong tadbir urus air yang bersepadu, cekap sumber dan sensitif konteks, dengan mengimbangi permintaan dan bekalan semasa mengekalkan kelestarian ekologi. Pendekatan ini harus melibatkan langkah-langkah terdesentralisasi, disesuaikan secara tempatan yang menampung kepelbagaian teknologi, sosioekonomi dan alam sekitar benua, disokong oleh kerjasama rentas sempadan dan penyelarasan kawal selia yang harmoni.

DATA-DRIVEN MODELLING AND APPLICATION IN CIRCULAR ECONOMY: A EUROPEAN WATER EFFICIENCY STUDY

ABSTRACT

In 2007, the European Union pledged to become a water-efficient community, a crucial step towards sustainable development, yet progress is constrained by the absence of relevant benchmarking and scientific insight. Addressing this gap, this thesis models and evaluates water use, public water sector, and economic water cycle efficiency across European countries, integrating mathematical and statistical methods, economic theories, and circular economy principles. Europe's water resources face growing pressure from climate change, overexploitation, and pollution. Notwithstanding the importance of improving water efficiency in both demand and supply to strengthen water security, advancements are impeded by a lack of assessment tools and research-based guidance tailored to diverse conditions. Moreover, despite efforts to adopt circular economy practices, there is substantial untapped potential, particularly exemplified by Germany. In response, the objectives of this thesis are to introduce frameworks for assessing water utilisation and sector efficiency across Europe, equipping stakeholders with decision-support instruments and insights to guide performance optimisation and facilitate cross-border learning, and to pioneer a comprehensive resource circularity-based assessment approach to inform holistic water economy performance improvements. This thesis examines water use efficiency, including contextual factors, based on cluster analysis and a total-factor parametric metafrontier model that accounts for water quality, drawing on European country-level panel data from 2011 to 2020. It also benchmarks public water sector efficiency across European countries using a non-parametric dynamic network modelling method, complemented by statistical analysis of external determinants, with panel data spanning 2013 to 2020. Moreover, the thesis introduces an unprecedented non-parametric looplike efficiency evaluation approach and applies it to study Germany's water economy at the regional level. The results show that there are considerable efficiency disparities across Europe, with technological progress driving performance gains. In addition, based on the findings, efficiency enhancements require targeted water sector restructuring, such as infrastructure upgrades, including in Germany. Furthermore, conservation-oriented areas excelling in sustainability may lag in efficiency, necessitating a focus on prudent land use planning and compatible modernisation. To assist policymakers and other decision-makers in navigating Europe's mounting water challenges and ensuring water security and sustainable development, this thesis advocates for integrated, resource-efficient and context-sensitive water governance, balancing demand and supply while upholding ecological preservation. This should involve decentralised, locally adapted measures that accommodate the continent's technological, socioeconomic, and environmental heterogeneity, supported by transboundary cooperation and harmonised regulatory oversight.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Water is both an irreplaceable natural as well as a strategic economic resource (Zheng et al. 2018) which is indispensable for life on Earth and plays a crucial role in socioeconomic progress (Luo et al. 2018; Yang et al. 2021). Moreover, as stated by Wang et al. (2018), responsible water governance constitutes a cornerstone for sustainable development, and to ensure that this vital resource remains available for current and future generations, the World Summit on Sustainable Development (WSSD) in 2002 acknowledged the importance of efficient water production, provision and consumption "in a way that gives priority to the satisfaction of basic human needs and balances the requirements of preserving or restoring ecosystems and their functions, in particular in fragile environments, with human domestic, industrial and agricultural needs, including safeguarding drinking water quality" (United Nations 2002). In its original sense, the principle of sustainability relates to the perseverance of natural conditions, from which it follows that sustainable development targets the improvement of living standards without wasting natural capital (Lynam and Herdt 1989; Turner 1993; Zhou et al. 2018a; Tsaples and Papathanasiou 2021). Accordingly, in the context of this thesis, higher efficiency is in accordance with lower water scarcity and less degradation of nature, as well as better utilisation of available technology, in turn serving to help free up resources and enhance overall productivity.

1.1.1 Research background

1.1.1(a) Foundations of European water governance

Owing to the sensitivity of water in terms of its role as a natural and economic resource, and the pressure to which it is exposed, the European Union (EU) in 2000 adopted the Water Framework Directive (WFD) with a view to safeguarding the ecological status of water bodies and advocating sustainable water use in EU member states. The WFD is the central piece of EU water policy and management regulation (European Commission 2020b; European Commission 2021). In addition, the EU in 2007 proposed a set of measures to move the community towards a water-efficient and water-saving economy (European Commission 2020b; European Commission 2021). Similarly, the European Innovation Partnership (EIP) for Water, which was launched in 2012, supports integrated water resource governance regarding water recycling and reuse – including the recovery of residuals, ecosystem services, and innovative management solutions, to "build an economy that is cleaner, greener and more efficient" (European Commission 2015). In fact, to foster sustainable development through improvements in resource efficiency based on recovery, recycling, and reuse (Ellen MacArthur Foundation 2013a; Ellen MacArthur Foundation 2013b; Korhonen et al. 2018; Patti 2023), the EU has pledged to progressively adopt circular economy practices, although the transition remains in its nascent stages (Ghisellini et al. 2016; Stahel 2016; Geissdoerfer et al. 2017; Kirchherr et al. 2017; Korhonen et al. 2018; Eisenriegler 2020; Nikolaou et al. 2021; Szczygieł 2021; Qtaishat et al. 2022; Chennak et al. 2023; Patti 2023; OECD 2024a). Furthermore, the EU has committed to the sustainable development goals (SDGs) of the United Nations (UN) in an attempt to synchronise corresponding efforts across its members (Adler 2011). In this regard, the present thesis pertains above all to the SDG targets 6.3, 6.4, 6.5 and 6.6 concerning mainly water recycling and reuse, water use efficiency and withdrawals, integrated water resource management, as well as the protection and restoration of water-related ecosystems, respectively (cf. United Nations 2024a).

1.1.1(b) Water challenges in Europe

1.1.1(b)(i) General considerations

Europe faces water-related challenges from climate change and extreme weather events (EEA 2017; The Nature Conservancy 2020; United Nations 2020; EEA 2021a; EEA 2021b; WAREG 2021; National Geographic 2022; Grafton et al. 2023; WWF 2023; EEA 2024; EurEau 2024; OECD 2024b). Based on a UN report, the areas of Europe under water stress due to climate change and the number of people affected by this issue are expected to grow in the decades to come (United Nations 2007). Climate change disrupts the hydrological cycle, leading to more frequent and prolonged droughts and floods, affecting the quantity and quality of freshwater resources with varying regional impacts (UNEP 2012; El Khanji and Hudson 2016; Dinar and Tsur 2021; EPA 2024). In particular, regions associated with low rainfall, high population density, or intensive agricultural or industrial activity may face water availability and sustainability issues in the coming years (European Commission 2020b).

Furthermore, excessive water abstraction for public supply, industry, and irrigation exerts considerable pressure on the quantity of freshwater resources in Europe, while contamination from household sewage, industrial effluents, and agricultural runoff degrades water quality (EEA 2017; EEA 2018; The Nature Conservancy 2020; United Nations 2020; EEA 2021b; EEA 2021a; WAREG 2021; National Geographic 2022; EEA 2023; Grafton et al. 2023; WWF 2023; EEA 2024; EurEau 2024; European Commission 2024; OECD 2024b). A large part of the water withdrawn for domestic, agricultural or industrial use is returned to the environment and its water bodies, albeit often as wastewater with impaired quality (European Commission 2020b).

Meanwhile, more frequent climate extremes reduce the predictability of water availability, thereby complicating the delivery of reliable water services (EEA 2017; The Nature Conservancy 2020; EEA 2021a; EEA 2021b; WAREG 2021; World Bank 2021; EEA 2024; EurEau 2024; OECD 2024b). In addition, outdated infrastructure in many parts of Europe threaten water security and sustainability, necessitating substantial investment to ensure efficient services (The Nature Conservancy 2020; EEA 2021a; EurEau 2021; WAREG 2021; World Bank 2021; EEA 2024; EurEau 2024; OECD 2024b).

1.1.1(b)(ii) Circular economy perspective

A circular economy promotes sustainable production and consumption by enhancing resource efficiency through recovery, recycling, and reuse (Ellen MacArthur Foundation 2013a; Ellen MacArthur Foundation 2013b; Korhonen et al. 2018; Patti 2023). Analogous to such a waste-reducing, regenerative system, and unlike natural recurring phenomena, the economic water cycle is a human-designed, closed-loop process where water is continuously reused (Korhonen et al. 2018; Nika et al. 2020).

Although the EU's Circular Economy Action Plan advocates for efficient and sustainable water management through resource recycling and reuse (UNEP 2012; EEA 2019; European Commission 2020a; EEA 2021a; Qtaishat et al. 2022; UNEN 2023), there is still substantial untapped potential to improve such practices in Europe (European Commission 2015). Germany in particular confronts severe obstacles in this respect (Chennak et al. 2023). Notably, Germany is struggling to optimise its water economy performance and adopt sustainable water management practices, partly due to a failure to invest in modernisation (Lewicka et al. 2023; UBA 2023; EEA 2024). Germany contends with infrastructure underinvestment, threatening supply, as well as declining water levels and regional water shortages driven by climate change and high water consumption, while increasing pollution jeopardises clean water provision, complicates wastewater treatment, and intensifies conflicts over water use (BDEW 2015; Cullmann et al. 2022; UBA 2023; Singh et al. 2023; EEA 2024). At the same time, Germany’s historical reliance on built water infrastructure and inadequate water and land management at the expense of environmental conservation have led to ecological degradation, including damaged freshwater ecosystems, prompting calls for re-naturalisation (Kang 2022; WWF 2023).

1.1.1(c) Need for action

Enhancing water efficiency and sustainable management practices are essential to addressing Europe’s water challenges (Zhu 2015; EEA 2018; United Nations 2020; Dinar and Tsur 2021; EEA 2021b; World Bank 2021; National Geographic 2022; Grafton et al. 2023; EEA 2024; OECD 2024b). To this effect, in a letter to the European Commission, dated 17th July 2024, a total of 21 European ministers collectively wrote (Water Europe 2024): “Increasing regions in Europe are already facing a limitation of natural freshwater resources which have become insufficient to meet water demands.” According to the ministers, this challenge requires “ensuring efficiency in supply and demand” and a willingness to “invest in ample cross-border infrastructure” in order to “strengthen water resilience across the Union.” The ministers request that these efforts must proceed “in a fair and equitable manner which respects the diverse hydrological and hydrogeological environment of Europe.” In addition, the letter states: “Strengthening water management in the European Union will require a strategic mobilisation of knowledge, technology and innovation, integrated planning and management tools, and monitoring (availability, consumption).” Indeed, relevant evaluation efforts are still in their infancy, as Europe lacks appropriate measurement frameworks and comparative analyses (UNEP 2012; EEA 2019; European Commission 2020a; EEA 2021a). Consequently, while cross-national comparisons play a vital role in gaining a comprehensive grasp of sustainability issues by providing countries with the opportunity to learn from each other's experiences (Tsai et al. 2016), insufficient scientific insights have hindered the EU's ability to conduct an adequate assessment of its progress towards SDG 6 (Žabkar and Redek 2020).

In anticipation of the problem statement in the next section, and the subsequent research questions and objectives, it is essential to recognise that Europe's water security challenges from climate change, overexploitation, and prevailing land use practices necessitate sustainable water management approaches that emphasise resource efficiency while accounting for local socioeconomic dynamics and broader contextual factors (United Nations 2014; Dinar and Tsur 2021; United Nations 2021a; Water Europe 2023; Fullerton 2024). In fact, water use efficiency is influenced by a range of exogenous factors, including socioeconomic conditions (Deng et al. 2016; Ma et al. 2017; Luo et al. 2018; Wang et al. 2018). Notably, living standard improvements through built infrastructure, human settlement in cities, and industrialisation are closely related to the issue of water use efficiency (United Nations 2021a), while innovative resource use practices can contribute to societal progress (cf. Callejas Moncaleano et al. 2021). Moreover, as noted by the European Commission (2020b), variations in freshwater abstraction across EU member states, are driven by factors such as country size, resource availability, abstraction practices, climate, and economic structure. Similarly, a variety of exogenous factors can influence water sector performance (Berg and Marques 2011; Carvalho et al. 2012; Molinos-Senante et al. 2015b; Pinto et al. 2017; Molinos-Senante et al. 2018; Sala-Garrido et al. 2021b).

Additionally, the interconnected challenges in Germany underscore the need to strengthen its circular economy and broader water management practices to align with sustainability objectives (BDEW 2015; EEA 2018; The Nature Conservancy 2020; EEA 2021a; Cullmann et al. 2022; BMUV 2023a; BMUV 2023b; EEA 2023; Lewicka et al. 2023; Singh et al. 2023; EurEau 2024). Even the German water industry, which generally assesses its own performance in public water provision and wastewater treatment favourably, has conceded existing shortcomings (BDEW 2020), aligning with broader concerns regarding water-related issues in Germany. In particular, the European Commission has urged Germany to adopt a comprehensive approach to water governance and update its infrastructure with a view to mitigating the impacts of extreme weather events, preventing freshwater depletion and scarcity, and addressing pollution to maintain water quality for safe drinking water and ecosystem protection across all regions (UBA 2023; EEA 2024; OECD 2024b).

1.1.2 Research framework

1.1.2(a) Theoretical and conceptual orientation

This thesis examines critical water demand and supply challenges in Europe, focusing on water utilisation and water sector issues, including secondary supply through wastewater conversion, as well as Germany's water economy. It is noteworthy that reusing treated wastewater enhances supply and alleviates pressure on overexploited resources, especially in water-stressed areas (UNEP 2012; EEA 2019; European Commission 2020a; EEA 2021a). Therefore, the thesis incorporates wastewater treatment into its analysis, acknowledging the sewage sector's role in resource efficiency through recycling and re-supply, while recognising sludge as a potentially valuable by-product, in line with circular economy principles.

To model and evaluate water use and public water service efficiency, as well as economic water cycle efficiency, this thesis integrates mathematical and statistical methods, economic theories, and circular economy principles. It employs resource, environmental and development economics to form the underlying theoretical framework and elucidate efficiency outcomes, with production theory, especially efficiency analysis, mainly serving to model and measure performance. The core methodology for this thesis is grounded in the principle of technical efficiency analysis with frontier functions serving as benchmarks to measure the performance of various production units. The benchmark is built from the most efficient units in the sample, which are on the production frontier due to their ability to maximise output from given inputs or minimise inputs for a certain output.

From the previous exposition, it is evident that efficiency analysis in the context of sustainability is a multidimensional task which requires the integration of different types of indicators, in particular socioeconomic and environmental ones. In addition, in view of the challenge to reconcile the goals of socioeconomic progress and environmental protection (Moutinho et al. 2017; lo Storto 2018; Sarkhosh-Sara et al. 2020; Wang et al. 2021), cross-national comparisons play a crucial role in understanding sustainability comprehensively, allowing countries to learn from one another's experiences (Tsai et al. 2016). To this effect, and given the importance of accounting for technological differences and group countries accordingly (Lin and Du 2013; Molinos-Senante and Sala-Garrido 2016; Ganhadeiro et al. 2018; Yu et al. 2018; Zheng et al. 2018) to enable tailored decision-making advice fitting specific circumstances (Sarkhosh-Sara et al. 2020), this thesis conducts a multidimensional pan-European evaluation of water use performance that considers variations in production technologies. Furthermore, potential determinants of efficiency are explored to gain deeper insights into factors influencing performance in Europe. In a further step, the present thesis benchmarks public water sector performance across European countries. To provide comprehensive insights into public water sector performance dynamics, the modelling framework integrates an assessment of the interaction between two subsystems, public water provision and wastewater treatment, while also gauging the effects of intertemporal links. This is complemented with a statistical analysis to explore how context variables influence efficiency.

Moreover, this thesis introduces a resource circularity-based dynamic network framework, viewing water as a limited natural resource that requires prudent holistic management with respect to infrastructure, production, consumption, cleaning, recycling and reuse (see Figure 1.1).

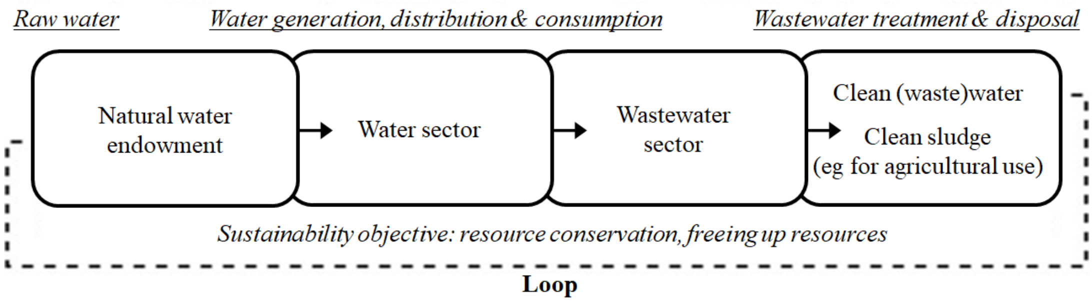

Figure 1.1 Circular concept for holistic water economy analysis

The proposed approach is applied to analyse intertemporal water economy performance across German federal states with regard to public water provision, wastewater services and natural water endowment, while accounting for water demand and infrastructure aspects, within a unified feedback system. To the best of the author's knowledge, no work to date has attempted to add a comparable circular connotation to efficiency modelling.

1.1.2(b) Organisation of thesis

This thesis initially focuses on the demand side, specifically water use, before transitioning to the supply side, which includes public water provision and sewage services. The final step involves a broader, combined investigation based on a comprehensive circular technical eco-efficiency analysis.

To facilitate reader orientation, in the remainder of the thesis, the themes that correspond to the three building blocks of resource demand, resource supply, and resource circularity, respectively, are referred to as:

- *Pan-European water utilisation benchmarking*
- *Pan-European public water sector benchmarking*
- *Economic water cycle benchmarking with the example of Germany*

Resource demand-related theme: pan-European water utilisation benchmarking. This thesis conducts a multidimensional pan-European water use performance evaluation. This study takes into account differences in production technologies among European countries to measure water use efficiency within the scope of a total-factor parametric metafrontier framework with a Shephard distance function. Moreover, potential efficiency outcome determinants are investigated to gain a more profound understanding of performance-influencing factors in Europe. The empirical results are based on an analysis of country-level panel data spanning from 2011 to 2020. Arguably, the present work constitutes the first comprehensive cross-country investigation for Europe of its kind.

Resource supply-related theme: pan-European public water sector benchmarking. This thesis undertakes a water supply-related pan-European performance benchmarking evaluation of the public water sector. The proposed model considers the interaction between two connected subsystems and the effects of intertemporal links, which has been mostly ignored in previous studies, to assess country-level water sector efficiency. Specifically, the water sector can be separated into a water provision component and a wastewater treatment component, and an assessment technique for the component, period, and component-period efficiencies alongside overall water sector efficiency is established. Further, a statistical analysis is conducted to explore potential external efficiency influencing factors. The empirical results are based on examination of panel data across 26 European countries in the period from 2013 to 2020. To the author's knowledge, this is the first pan-European comparative study of its kind in the field.

Holistic resource circularity-related theme: economic water cycle benchmarking with the example of Germany. This thesis proposes a technical efficiency evaluation approach that incorporates the idea of resource circularity to study the water economy. The suggested approach is unprecedented in its simultaneous analysis of public water provision, wastewater services and natural water endowment, while taking water demand into account. It also addresses the issues of water sector infrastructure and environmental sustainability. To the author's knowledge, no comparable study to address full-scale circular water economy modelling including the objectives of resource conservation and optimisation of water sector infrastructure utilisation has yet been published.

It is worth noting that, given their geographic scope and examination of regional contexts and challenges across Europe, both the water utilisation analysis and the public water sector investigation, covering 29 and 26 European countries, respectively, are regarded as 'pan-European' studies.

The remainder of this chapter contains the problem statement in the next section and addresses the research questions, objectives and significance in the following sections. Chapter 2 reviews relevant prior literature. Chapter 3 describes the methodology, including information on samples and data. Chapter 4 reports and discusses the empirical results. Chapter 5 concludes the thesis.

1.2 Problem statement

Water, a vital yet limited resource for economies and ecosystems, faces critical challenges in Europe due to climate change, excessive extraction for public, industrial, and agricultural use, and unsustainable land use practices, while pollution from residential activities, manufacturing and farming degrades quality and complicates sustainable supply. Improving water efficiency in demand and supply is essential to ensure Europe's water security, yet a lack of appropriate benchmarking and scientific insights, including international comparison, leaves progress unmeasurable.

To further motivate the following research questions and objectives, it is important to acknowledge that water use efficiency and water sector performance are influenced by a range of contextual factors, including local socioeconomic conditions, infrastructure development, and resource management practices. Moreover, variations in freshwater abstraction across Europe due to factors such as country size, resource availability, abstraction practices, economic structure, and climate further underscore the impact of diverse country-specific characteristics.

In addition, the EU aspires to enhance efficient and sustainable water management in line with its Circular Economy Action Plan, but there remains considerable untapped potential. Germany in particular faces challenges in this respect, struggling with outdated and strained infrastructure due to underinvestment, which threatens reliable supply of clean water and complicates wastewater treatment, as well as ecological harm from historical reliance on built water systems. Climate change, local water shortages, and contamination from intensive water use further increase Germany's need for modernised, sustainable water management practices.

European countries' common goal of establishing a water-efficient community, shared challenges, and varying national circumstances underscore the need for a benchmarking approach that enables both comprehensive and targeted guidance regarding sustainability-oriented water governance across the continent. Moreover, addressing the interrelated challenges in Germany requires the identification of water economy inefficiencies and optimisation opportunities across the nation based on holistic benchmarking and analysis.

1.3 Research questions

Building upon the research background and problem statement outlined above, the research questions guiding the investigation in line with the core themes of this thesis are:

Pan-European water utilisation benchmarking

- How can total-factor water use efficiency, technology gaps, and the impact of potential water resource utilisation efficiency determinants be measured and evaluated, while also accounting for water quality, within a pan-European sustainability context?
- What comparative insights can be derived for water resource sustainability-related policy formulation in Europe?

Pan-European public water sector benchmarking

- How can the overall water sector, water provision and wastewater treatment efficiencies be simultaneously assessed under dynamic conditions, while also exploring the impact of potential efficiency determinants, within a pan-European context?

- What comparative water sector insights can be gained for policy decision-making and water management practices in Europe?

Economic water cycle benchmarking with the example of Germany

- How can distinct yet interrelated water economy processes be unified under a circular efficiency evaluation paradigm to underpin holistic, environmentally-prudent water resource management concerning infrastructure, production, consumption, cleaning, as well as recycling and reuse?
- Which insight into economic water cycle dynamics can the measurement within a looplike context of divisional efficiencies in addition to composite network efficiency over time provide?

1.4 Research objectives

Addressing Europe's water-related challenges requires improved efficiency in demand and supply, supported by benchmarking and international comparison. Hence, this thesis develops corresponding frameworks and evaluates water use and sector performance across Europe, offering decision-support tools for informing efficiency enhancements, while facilitating international comparison and learning, to support sustainable development. As the reuse of treated wastewater reduces pressure on overexploited resources, this thesis integrates wastewater treatment into its analysis, recognising the sewage sector's contribution to resource efficiency through recycling and re-supply. Furthermore, while the EU aims to align water governance with circular economy principles, untapped potential remains, particularly in Germany, necessitating holistic benchmarking to guide efficiency-oriented, sustainable water management practices. Therefore, this thesis introduces a comprehensive resource circularity-based efficiency assessment framework which is applied to provide insights into Germany's water economy performance and identify corresponding optimisation opportunities at the regional level.

To this effect, and in view of the above research questions and problem statement, as well as the underlying research background, the research objectives of this thesis in line with its core themes are:

Pan-European water utilisation benchmarking

- To measure and evaluate total-factor water use efficiency, technology gaps, and the impact of potential water resource utilisation efficiency determinants, while accounting for water quality, within a pan-European sustainability context.
- To derive relevant comparative insights for resource sustainability-related policy formulation.

Pan-European public water sector benchmarking

- To simultaneously assess the overall water sector, water provision and wastewater treatment efficiencies under dynamic conditions, while also exploring the impact of potential efficiency determinants, within a pan-European context.
- To offer relevant comparative water sector insights for policy decision-making and water management practices.

Economic water cycle benchmarking with the example of Germany

- To unify distinct water economy processes under a circular efficiency evaluation paradigm with a view to underpinning holistic, environmentally-prudent water resource management concerning infrastructure, production, consumption, cleaning, as well as recycling and reuse.

- To provide relevant insight into economic water cycle dynamics based on the measurement of divisional and composite network performance over time within a looplike context.

1.5 Significance of research undertaken

Improving water efficiency in demand and supply is essential to addressing Europe's challenges, but appropriate measurement frameworks and comparative analyses are absent (UNEP 2012; EEA 2019; European Commission 2020a; EEA 2021a). In fact, insufficient scientific insights, including international comparison, leaves the EU's progress towards SDG 6 unmeasurable (Žabkar and Redek 2020). This thesis makes a theoretical contribution by introducing comprehensive decision-support models for pan-European water use and sector efficiency analysis, providing a foundation for cross-country benchmarking and learning.

This thesis conducts a multidimensional, total-factor pan-European water use performance evaluation accounting for differences in production technologies. Moreover, potential efficiency outcome determinants are investigated to gain a profound understanding of performance-influencing factors in Europe. The thesis explicitly incorporates water quality into the evaluation framework, offering an additional theoretical contribution to the literature, while also considering the type of resource usage in the analysis. This work arguably constitutes the first comprehensive Europe-wide cross-country analysis of its kind. It provides more encompassing and instructive findings than prior studies that have typically relied on partial-factor indicators with limited explanatory power.

This thesis also evaluates public water sector performance across European countries to inform relevant policy formulation and management practices. The modelling framework adopted for this purpose considers the interaction between two subsystems, namely public water provision and wastewater treatment, and the effects of intertemporal links. Moreover, a statistical analysis to explore the influence of context variables is performed. To the author's knowledge, this work constitutes the first pan-European study in the field.

Furthermore, the thesis adds to the academic literature by going beyond previous models to introduce a modelling approach allowing for the simultaneous evaluation of public water provision, water consumption, wastewater services, and natural water endowment efficiency, while also addressing infrastructure issues, in a unified, time-sensitive feedback framework. To the author's knowledge, despite ongoing efforts to advance sustainable practices, no comparable work attempting to introduce a circular connotation to efficiency modelling and guide holistic, environmentally-responsible water governance exists thus far.

1.6 Concluding remarks

In 2007, the EU declared its intention to become a water-efficient community. Yet, despite the community's commitment to the UN SDGs, relevant insight based on scientific research is still sparse. Addressing this void, this thesis presents a total-factor pan-European water use performance evaluation, considering differences in production technologies and potential exogenous efficiency determinants. Versus prior studies that have typically relied on partial-factor indicators with limited explanatory power, the thesis provides more instructive and encompassing findings to inform holistic policy formulation and management practices. Arguably, this comparative benchmarking analysis constitutes the first comprehensive cross-country investigation for Europe of its kind. This thesis also performs an evaluation of water sector efficiency across European countries. The objectives are to simultaneously assess overall water sector, water provision and wastewater treatment performance under dynamic conditions, while also exploring the impact of contextual performance determinants, and to offer relevant comparative insights to guide policy decision-making and water management practices. To the author's knowledge, this is the first pan-European study of its kind. Finally, this thesis breaks new ground by introducing a novel, looplike dynamic network framework capable of unifying distinct yet interrelated processes under a technical efficiency paradigm that obeys circular economy principles. The proposed framework, which enables – arguably for the first time – simultaneous analysis of public water provision, water demand, wastewater services, natural water endowment, and infrastructure aspects in an encompassing feedback-type context, is applied to assess Germany's water economy performance at the federal state level. Given ongoing attempts to promote sustainability-oriented circular practices, this analysis can offer water economy stakeholders with timely and wide-ranging guidance.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a review of the relevant literature for the present research. As stated above and highlighted in the next section, this thesis integrates resource, environmental, and development economics, as well as production theory, to establish a strong theoretical foundation for water efficiency analysis concerning Europe. Moreover, the literature review draws on studies relating to water benchmarking from diverse geographical regions and contextualises their findings in line with the three main themes of the thesis regarding water utilisation, public water sector, and economic water cycle performance evaluation. The literature review also includes a synopsis that summarises existing research gaps and provides and overview of the contributions of this thesis across its three central themes.

2.2 Theoretical underpinnings

2.2.1 Resource, environmental, and development economics

Integrating resource, environmental, and development economics is essential to understanding efficient and sustainable water governance. This combined perspective underscores the need to balance economic growth with environmental preservation (Harris and Roach 2021) and provides insights into how socioeconomic and other contextual factors shape water efficiency and sustainable development (Zhu 2015; Todaro and Smith 2022; Water.org 2024). In its original sense, the principle of sustainability relates to the perseverance of natural conditions, from which it follows that sustainable development targets the improvement of living standards without squandering environmental resources (Turner 1993; Zhou et al. 2018a; Tsaples and

Papathanasiou 2021). In fact, according to Sarkhosh-Sara et al. (2020), every nation strives for an increase in the value of production while aiming to optimise the use of resources and reduce environmental impacts. Recent exemplary studies covering such settings as supply chain management (Sarkar and Seo 2021; Garai and Sarkar 2022; Sarkar et al. 2022a), production operations with recoverable materials (Wu et al. 2016; Cook et al. 2020; Sarkar et al. 2022c), energy creation (Sarkar et al. 2022b), marine circular economy (Ding et al. 2020b) and more general industrial circular systems (Sun et al. 2019; Ding et al. 2020a; Chen et al. 2021) attest to this notion. That said, balancing resource scarcity, economic progress, and environmental protection is a multifaceted task that involves managing various indicators to minimise ecological resource use and reduce environmental impacts while maximising goods and services production (Sarkhosh-Sara et al. 2020; Wang et al. 2021).

While maintaining the sustainability of water resources constitutes the main objective of water resource management (Mays 2013), and an adequate evaluation framework can assist in promoting awareness of sustainable water usage (Ding et al. 2019b), according to Zheng et al. (2018), improving water efficiency and understanding its determinants is a key task in achieving resource use and socioeconomic sustainability. Moreover, the target of improving water use efficiency is consistent with the promotion of water conservation in agriculture, industry and residential consumption (Pereira et al. 2012). As such, more efficient water use coincides with the overall pursuit of resource sustainability and sustainable development (Baumann et al. 1998; Bithas 2008; Halkos and Tzeremes 2012; OECD 2012; United Nations 2015; Luo et al. 2018; Zheng et al. 2018; Lombardi et al. 2019; Walker et al. 2019). Additionally, water sector performance benchmarking and resulting industry governance and efficiency improvements may contribute to sustainable development (Molinos-Senante et al. 2016; Molinos-Senante et al. 2018).

European regions facing low rainfall, high population density, or intensive economic operations are increasingly vulnerable to water scarcity, a challenge exacerbated by climate change, necessitating resource-efficient management prioritising reuse to decouple economic growth from consumption (United Nations 2014; European Commission 2020b; Dinar and Tsur 2021; United Nations 2021a; Water Europe 2023; Fullerton 2024). In this respect, efficient wastewater treatment plays a vital role in balancing development and ecosystem protection (Guerrini et al. 2013; Ma et al. 2016b; Ma et al. 2022; United Nations 2024c), particularly as socioeconomic advancements, while improving access to essential infrastructure and technologies for resource optimisation, simultaneously increase demand and strain existing supply and treatment capacities (UNEP 2012; Zhu 2015; Adams et al. 2016; El Khanji and Hudson 2016; Ma et al. 2016b; Dinar and Tsur 2021; Harris and Roach 2021; World Bank 2021; Todaro and Smith 2022; Grafton et al. 2023; Singh et al. 2023; EPA 2024; OECD 2024b; United Nations 2024c).

The protection of water resources to promote sustainable development also entails the preservation of water quality. Indeed, economic growth, water consumption, and water quality are intricately linked, because human activities such as industrial production, household discharges or arable farming not only affect water quantity but also water quality by contributing to the pollution of rivers, lakes and groundwater (United Nations 2014; Nzilano 2017; NAP 2019; European Commission 2020b; Callejas Moncaleano et al. 2021; United Nations 2021a; UNEN 2023; WEF 2023). For instance, El Khanji and Hudson (2016) analysed water use and quality in 177 countries from 1960 to 2009, identifying water scarcity and contamination as a growth constraint in major economies like China, India, and Indonesia, and advocating for efficient water use and improved water quality to support sustainable development. Accordingly, besides water use efficiency and corresponding changes in water extraction and consumption practices, a key water management issue in Europe concerns drinking water quality (European Commission 2021).

Water quality is intrinsically linked to production processes and technological choices (UNEP 2012; El Khanji and Hudson 2016; EPA 2024), as high-quality water enhances efficiency by minimising treatment needs, whereas poor quality necessitates costly advanced treatment, thereby reducing efficiency (UNEP 2012; El Khanji and Hudson 2016; EPA 2024). Moreover, technological advancements in wastewater treatment are crucial for mitigating contamination and improving water quality, but these solutions often entail substantial upfront investments (UNEP 2012; El Khanji and Hudson 2016; Ma et al. 2016b; EPA 2024). Furthermore, water quality is closely tied to socioeconomic factors. Notably, higher living standards, urbanisation, and industrialisation are often associated with better wastewater treatment technology and water quality but also amplify resource depletion and pollution risks, requiring effective pollution control with a view to promoting socioeconomic development while safeguarding ecosystems (UNEP 2012; Zhu 2015; El Khanji and Hudson 2016; United Nations 2020; Dinar and Tsur 2021; World Bank 2021; Grafton et al. 2023; EEA 2024; EPA 2024; OECD 2024b). To this effect, balancing economic growth and environmental preservation requires adaptable built and ecological infrastructure (e.g., treatment plants and natural catchments) and land use compatibility with water bodies to mitigate surface sealing impacts and safeguard essential water-related ecosystem services – including wetlands' water filtration and purification capabilities (Zhu 2015;

HLPW 2018; EEA 2019; United Nations 2020; Callejas Moncaleano et al. 2021; EEA 2021a; BMUV 2023b; EEA 2023; Grafton et al. 2023; OECD 2024b).

2.2.2 Production theory and technical efficiency analysis

Production theory, encompassing technical efficiency analysis, provides the foundation for analysing the transformation of inputs into outputs and the corresponding role of production technologies and frontiers (Farrell 1957; Färe et al. 1994; Rasmussen 2013; Varian 2019; Ray et al. 2022). These principles are integral to benchmarking based technical efficiency analysis using parametric and non-parametric methods (Färe et al. 1994; Thanassoulis 2000; Coelli et al. 2005; Peterson and Hendricks 2018; Ray et al. 2022; Grafton et al. 2023). The origins of the concept termed as 'technical efficiency' in production which describes the optimal use of all the production factors in a production process, in accordance with the existing technology, can be traced back to the works of Debreu (1951) and Shephard (1953). Eventually, Farrell (1957), one of the first scholars to examine efficiency in production, pioneered the measurement of technical efficiency which may be thought of as a measure of the distance between the optimal production level on the production possibility frontier and the actual level adopted by a particular production unit. Accordingly, technical efficiency can be increased by producing more output with a given level of input or, alternatively, by producing a given level of output with fewer inputs. For instance, usable water supplies may be regarded as output. On the other hand, water may represent an input (e.g., in farming or manufacturing). In the latter case, technical efficiency equates to water-use efficiency (GWP 2006). Meanwhile, eco-efficiency, a key measure of sustainable development, aims to fulfil maximum human needs with minimum ecological resources (UNEP 1996). In considering production resources, economic benefits, and waste and pollution, eco-efficiency assessment is a multi-dimensional task that focuses on minimising resource use, maximising goods and services production, and reducing environmental impacts (Wang et al. 2021). Efficiency analysis in the above sense for water resources can be carried out either with a parametric approach, specifically stochastic frontier analysis (SFA), or with a non-parametric technique, in particular data envelopment analysis (DEA) (Cubbin and Tzanidakis 1998; Thanassoulis 2000; Abbott and Cohen 2009; Berg and Marques 2011; Worthington 2014; Lombardi et al. 2019; lo Storto 2020).

2.2.2(a) Parametric benchmarking technique

SFA is a parametric frontier technique developed by Aigner et al. (1977). It is a popular method to assess water use efficiency (Alem 2021). Unlike non-parametric methods, SFA can accommodate statistical noise in technical efficiency measurements by allowing for observations on both sides of the frontier, distinguishing between random errors and inefficiency differences (Mendes et al. 2013). SFA also enables the direct inclusion of external variables to investigate potential efficiency determinants (Zheng et al. 2018; Molinos-Senante and Maziotis 2019). Similar to non-parametric efficiency evaluation methods, SFA can involve multiple inputs and outputs (Bogetoft and Otto 2011). But due to the parametric formulation, SFA requires a pre-specified production function, i.e., specification of functional form, and specification of a distributional form for the inefficiency term (Bogetoft and Otto 2011).

Conventional estimation in SFA is based on one unified reference technology where all the countries participate in the evaluation with the same technological benchmark where the underlying technology is the same for all sample observations regardless of differences in the working environment (Alem 2021). However, there may exist technological heterogeneity among countries (Zhou et al. 2018a), which necessitates different technological benchmarks (Yu et al. 2018). That is, countries in