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Understanding water-energy-carbon nexus in English and Welsh water industry by assessing eco-productivity of water companies

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Understanding the water-energy-carbon nexus in water supply is essential for water regulators and utilities. This study employs a non-radial Data Envelopment Analysis (DEA) model to assess eco-productivity (ecoP) change, a synthetic indicator that integrates carbon emissions, energy costs, and water delivered. It also evaluates its components—eco-efficiency change and eco-technological change—across water companies in England and Wales from 2011 to 2018. The analysis reveals an annual improvement in ecoP of 1.1%, driven by a 2.1% gain in eco-efficiency but offset by a 1.0% decline in technological advancement. The reduction in GHG emissions emerged as the most significant positive contributor, enhancing ecoP by 3.22% annually, while energy costs detracted ecoP by –0.09%. The results underscore the negative impacts of increased water delivery (–1.74%) and the number of connected properties (–1.27%) on ecoP, highlighting the need for demand management policies.

The Sustainable Development Goals established by the United Nations in 2015[1] emphasize the critical nexus of water, energy, and carbon in achieving sustainable development by 2030. They specifically underline the importance of enhancing energy efficiency, promoting the sustainable use of energy and renewable resources (Goal 7), reducing greenhouse gas (GHG) emissions to deal with climate change (Goal 13), and ensuring the availability and sustainable management of water and sanitation for all (Goal 6). Despite these goals, a report by the International Energy Agency highlighted that the average rate of energy demand in 2018 was more than double that of 2010, largely driven by a strong economic growth[2]. Additionally, from 2010 to 2022, global GHG emissions increased by 9%, rising from 49,423 million tonnes per year to 53,851 million tonnes per year[3]. However, to meet the targets set by the Paris Agreement, it is necessary to reduce global GHG emissions by ~43% by 2030 and 60% by 2035 from 2019 levels, with the ultimate goal of achieving net-zero CO_2 emissions by 2050[4]. This underscores the need for transformative changes across all sectors, including water services[5].

The intricate interconnections between energy, carbon, and water are referred to as the water-energy-carbon nexus[6]. According to urban metabolism approach[7], within the context of cities, the water-energy-carbon nexus encompasses three interconnected components: the water system, the energy system, and the consumption system[8]. In the context of water provision, water utilities require energy for the abstraction, treatment, and distribution of water, which can result in significant GHG emissions and economic costs[9]. According to the Association of European Water Regulators[10], the energy intensity for water production varies between 0.34 kWh/m^3 and 0.82 kWh/m^3, while for water distribution, it ranges from 0.1 kWh/m^3 to 1 kWh/m^3. This energy consumption represents between 10% and 30% of the total annual costs incurred by water companies. Additionally, GHG emissions from the urban water sector contribute between 1% and 3% of a country's total emissions[11]. A comprehensive literature review by Zhang et al.[12] highlighted the scale of annual GHG emissions from drinking water systems across various countries: China reported emissions of 7.63 Mt CO_2 equivalent (CO_{2e}), Australia 1.11 Mt CO_{2e}, the United Kingdom 2.00 Mt CO_{2e}, and the United States of America 18.6 Mt CO_{2e}. These figures underscore the relevance of energy use and GHG emissions within the provision of drinking water services.

Efficiency and productivity analyses have long been staples in evaluating the performance of water utilities[13,14]. These analyses are crucial for water regulators, who in some regulations use the results to inform water

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tariff settings and identify potential improvements within the monopolistic industry framework. Traditionally, these analyses have focused primarily on the economic performance of water companies[15]. However, growing concerns over GHG emissions from water services have spurred the development of a new research focus: assessing the eco-efficiency and eco-productivity (ecoP) of water companies[16–19]. Unlike traditional efficiency and productivity estimations that concentrate solely on economic factors, eco-efficiency and ecoP analyses also incorporate GHG emissions associated with the provision of water services[20]. Complementing the studies on eco-efficiency and ecoP, a burgeoning research stream has emerged dedicated to assess the energy efficiency of water companies in their provision of water services[21–24].

To enhance the understanding of the water-energy-carbon nexus in water service provision, some studies have refined eco-efficiency analyses by integrating both energy use and GHG emissions. This approach leads to "improved" eco-efficiency estimations. While this approach is still in its early stages primarily due to data availability constraints, there are some exceptions which demonstrate the feasibility and potential benefits of integrating energy use and GHG emissions into the efficiency analyses of water services. Sala-Garrido et al.[25] assessed the eco-efficiency of English and Welsh water companies using cross-efficiency Data Envelopment Analysis (DEA) techniques. This analysis incorporated energy costs as inputs and GHG emissions as undesirable outputs. The case study developed by Molinos-Senante et al.[26]. utilized the DEA method to evaluate the "improved" eco-efficiency of water companies, with a specific focus on quantifying potential savings in energy costs and reductions in GHG emissions. Alternatively, Sala-Garrido et al.[27] employed the range-adjusted measure DEA method to assess and compare both carbon efficiency and production efficiency (excluding GHG emissions) of English and Welsh water companies.

The limited research estimating "improved" eco-efficiency of water companies, which integrates energy costs and GHG emissions, faces two primary limitations that our study aims to address. Firstly, from a methodological standpoint, previous studies predominantly used radial DEA methods, which do not allow for a detailed performance assessment of each variable included in the evaluation. This limitation restricts the ability to quantify the specific impacts of energy costs, GHG emissions, and other variables on the performance of water companies. Our study addresses this gap by employing the Weighted Russell Directional Distance Model (WRDDM), developed by Fujii et al. [28]. This non-radial DEA approach enables non-proportional reductions in inputs or augmentations in outputs, allowing for a more nuanced assessment of ecoP. Secondly, prior research focused on static measures of eco-efficiency, which do not capture changes in performance over time. Our study extends this by estimating the ecoP of water companies, incorporating a dynamic assessment that integrates the time dimension. This approach provides a more comprehensive understanding of how water companies' performance evolves, highlighting improvements or regressions in performance over time[29].

Against this background the main objectives of this study are fourfold. The first objective is to evaluate the ecoP of water companies, including its components - eco-efficiency change (ecoEC) and eco-technical change (ecoTC)- by integrating energy costs and GHG emissions using a non-radial DEA approach. The second objective is to quantify the impact of each variable integrated in the assessment (energy costs, other costs, GHG emissions, water delivered, and water connected properties) on ecoP, ecoEC and ecoTC of water services. The third objective is to compare the ecoP, ecoEC and ecoTC, as well as the contributions of each variable, between two types of water companies providing water services such as water only companies (WoCs) and water and sewerage companies (WaSCs). The fourth objective is to analyze the influence of a set on environmental variables on the ecoP of water companies.

This study presents significant advancements in the analysis of ecoP within the water services sector by integrating both energy costs and GHG emissions, areas previously unexplored together in this context. This pioneering approach enhances the understanding of the energy and carbon nexus with water service operations. By incorporating a non-radial DEA methodology, the research distinguishes itself further by allowing a detailed disaggregation and assessment of the contributions of individual variables to the ecoP, ecoTC, and ecoEC of water companies. This methodological innovation provides a more nuanced analysis that can identify specific areas of improvement. Consequently, this study not only contributes a novel analytical framework to the literature but also equips policymakers and industry stakeholders with a more precise tool for enhancing ecoP on water services.

The concept of eco-efficiency was introduced by the World Business Council for Sustainable Development (WBCSD) in the early 1990s. It is based on the principle of using fewer resources to produce more goods and services while simultaneously reducing waste and environmental pollution[30]. Building on this idea, the Organisation for Economic Co-operation and Development[31] defined eco-efficiency as "a ratio of an output (the value of products and services produced by a firm, sector, or economy as a whole) divided by the input (the sum of environmental pressures generated by the firm, the sector, or the economy)." In this context, eco-efficiency provides a conceptual framework for integrated analysis and assessment of socio-economic development[32]. Although there is no universally accepted definition of eco-efficiency that applies to all sectors, it is generally understood as an index of economic and environmental performance, contributing to sustainable development[33].

Within the water-energy-carbon nexus in water systems examined in this study, eco-efficiency serves as a metric for assessing the energetic, carbon, and economic performance of water companies. It is estimated using a synthetic indicator that integrates five key variables: energy costs, other operational costs, GHG emissions, the volume of drinking water delivered, and the number of connected water properties. This comprehensive metric offers a holistic assessment of water companies' performance in providing drinking water, reflecting their efficiency in managing resources while minimizing environmental impact.

Eco-efficiency is a static concept, meaning it provides information about the performance of units (such as water companies) at a specific point in time, without accounting for potential changes over time. To support decision-making, understanding the temporal dynamics of eco-efficiency is essential[34,35]. EcoP extends the notion of eco-efficiency to an intertemporal perspective[19]. Like eco-efficiency, EcoP is a synthetic indicator that provides insights into the economic, energetic, and carbon performance of water companies. However, unlike eco-efficiency, EcoP focuses on changes over time, allowing for the evaluation of whether policies or measures implemented by water companies have been effective in improving eco-efficiency or not.

Changes in EcoP can be driven by multiple factors, but from a methodological standpoint, these changes can be categorized into ecoEC and ecoTC. EcoEC evaluates the extent to which less efficient water companies have improved their eco-efficiency relative to the most efficient ones in the industry. It examines how these companies have adjusted their inputs (e.g., energy use) and outputs—both undesirable (e.g., carbon emissions) and desirable (e.g., water distributed)—to move closer to the performance of the most efficient companies. In contrast, ecoTC measures shifts in the efficiency frontier between two periods. It can be induced by an increase (or decrease) of the rate of transformation of inputs into outputs. This metric captures the degree of technical innovation within the industry.

Results and discussion

Eco-productivity and its components: eco-technical change and eco-efficiency change

Estimations of ecoP and its components—ecoTC and ecoEC—were conducted at the water company level, involving the resolution of Eqs. (3–10) for each assessed company using an iterative modeling approach. Due to the absence of a direct calculation method for ecoP and its components, providing more detailed steps of the estimations was not feasible.

From 2011 to 2018, the average ecoP of English and Welsh water companies improved by 1.1% per year, driven by an increase in ecoEC of

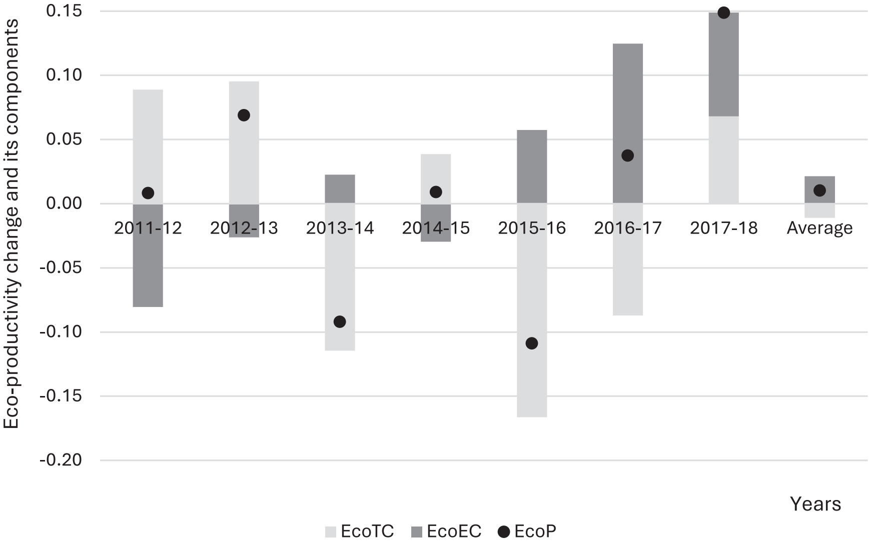


Fig. 1 | Evolution of the average eco-productivity change and its components of English and Welsh water companies. The dark gray bars signify eco-efficiency change (EcoTC), the light gray bars indicate eco-technical change (EcoEC), and the dots represent changes in eco-productivity (EcoP).

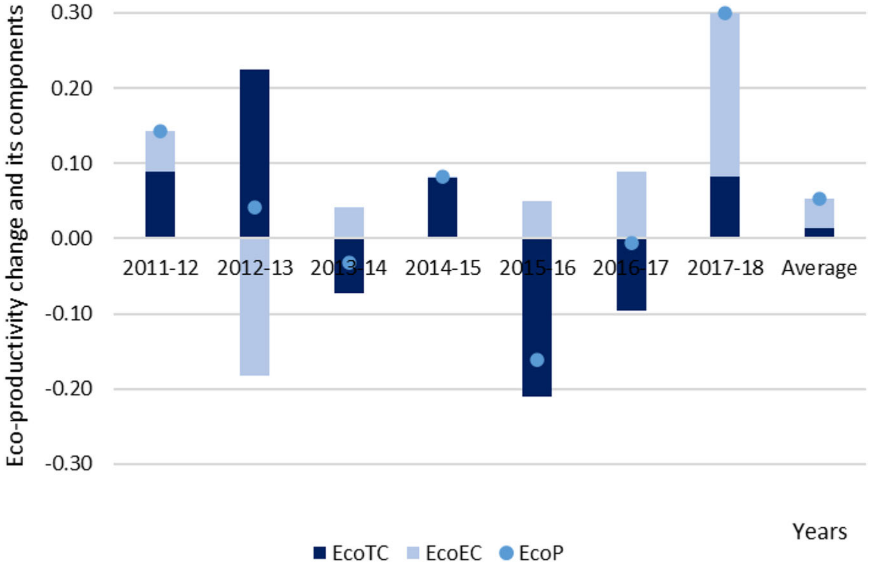


Fig. 2 | Evolution of the average eco-productivity change and its components of English and Welsh water only companies. The dark blue bars signify eco-technical change (EcoTC), the light blue bars indicate eco-efficiency change (EcoEC), and the dots represent changes in eco-productivity (EcoP).

2.1% per year. Conversely, ecoTC was negative, declining by 1.0% annually. This pattern indicates that, on average, less eco-efficient water utilities enhanced their performance towards the most efficient benchmarks in the industry. However, these gains in eco-efficiency were offset by technical regress. The trend of ecoP over the years (Fig. 1) was notably volatile. During the initial two years of the sample period (2011–2013), improvements in ecoP were attributed to technical progress, while eco-efficiency negatively impacted ecoP. This suggests that at the start of the period, water companies adopted the best available technologies aimed at reducing production costs and carbon emissions. However, inefficient resource allocation led to losses in eco-efficiency. Between 2013 and 2015, average ecoP deteriorated at a rate of 4.1% annually, primarily due to a decline in technology and inefficient management of daily operations, which contributed 3.8% and 0.3% to the downturn, respectively. A lack of technological leadership continued in subsequent years. From 2015 to 2018, technical regress of 6.2% per year adversely affected ecoP. Despite this, less eco-efficient water utilities managed to improve their performance relative to the most efficient ones, thereby enhancing ecoP. Eco-efficiency gains of 8.8% per year resulted in an average increase in ecoP of 2.6% during this period.

Overall, the ecoP results depicted in Fig. 1 show that the water industry achieved modest improvements in its performance from both technical and environmental perspectives. These enhancements were primarily attributed to gains in eco-efficiency, although there was significant technical regress. On average, the industry could enhance its ecoP by embracing technological innovation—specifically, by adopting new technologies that reduce production costs and carbon emissions while delivering water services. For instance, utilizing energy from renewable resources during the water treatment process could significantly reduce carbon emissions[36]. Additionally, optimizing energy use during the extraction of water from boreholes and the transportation of water to treatment facilities represents another best practice strategy[37,38].

Figures 2 and 3 present the results of ecoP and its determinants by type of company, i.e., WaSCs and WoCs. Results from 2011 to 2018 indicate that, on average, WoCs were more eco-productive than WaSCs. Specifically, the average WoC improved its ecoP by 5.3% per year, while WaSCs experienced an average ecoP decline of 1.9% per year. The productivity gains in WoCs were primarily due to increases in efficiency change and technical progress. This indicates that less eco-efficient WoCs not only caught up with the most efficient water utilities but also adopted new technologies. The annual rate of technical progress for WoCs was 1.4%, with ecoEC gains averaging 3.9% per year. In contrast, a lack of technological leadership was the primary factor contributing to the deterioration of ecoP in WaSCs. The differences in ecoP,

Fig. 3 | Evolution of the average eco-productivity change and its components of English and Welsh water and sewerage companies. The dark orange bars signify eco-technical change (EcoTC), the light orange bars indicate eco-efficiency change (EcoEC), and the dots represent changes in eco-productivity (EcoP).

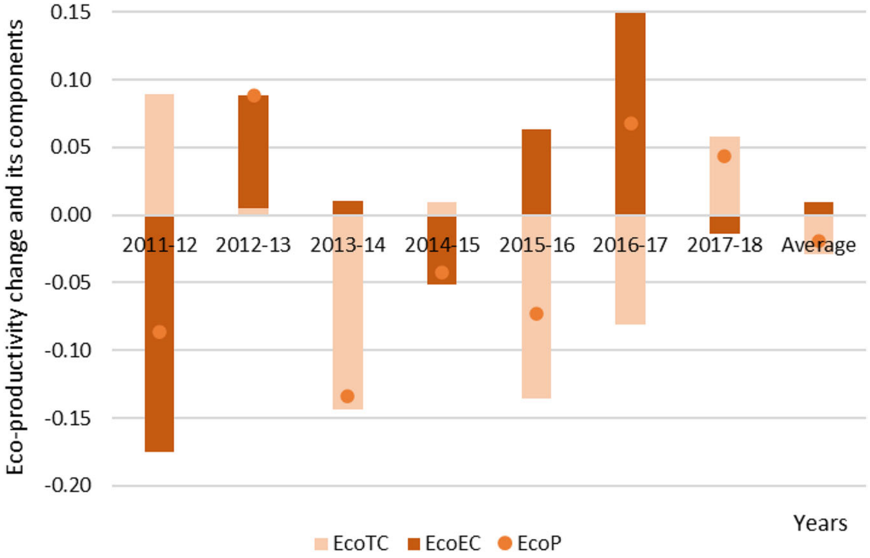
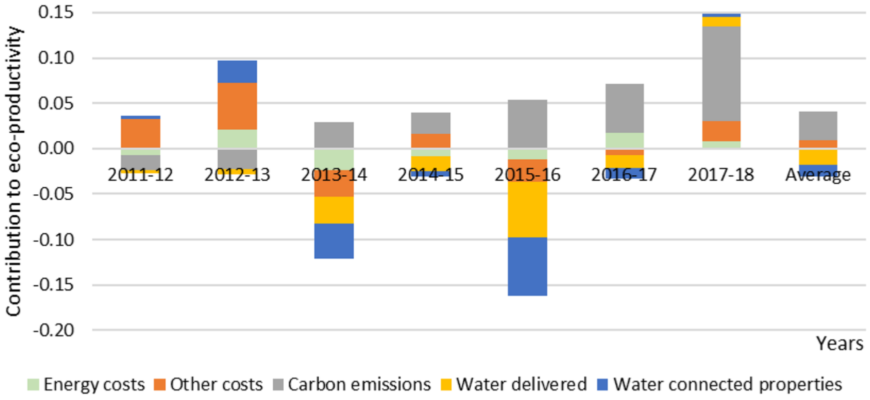


Fig. 4 | Contribution of each variable to eco-productivity change of English and Welsh water companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.



ecoTC and ecoEC between the two types of water companies were statistically significant, as indicated by the *p*-values of <0.05 from the Mann–Whitney test. Mann–Whitney is a non-parametric test that is used to compare two sample means that come from the same population, and used to test whether two sample means are equal or not.

Based on the trends observed in ecoP and its drivers for an average WoC (Fig. 2), it is evidenced that ecoEC was positive for most of the periods evaluated. Notable gains in eco-efficiency became apparent from 2013 to 2014 onwards, reaching peak levels during the years 2016–18. In contrast, ecoTC exhibited more volatility. While technology was advancing at an annual rate of 15.6% during 2011–2013, it followed a downward trend in subsequent years, which was interrupted during the 2017–2018 period. A similar trend in ecoTC was observed for an average WaSC (Fig. 3), but the magnitude of technical regress was considerably higher. Regarding ecoEC, WaSCs showed some gains in efficiency over time, though these were modest, averaging 0.9% annually. Any gains in eco-efficiency were offset by technical regress whose average value was –2.9%. Overall, WaSCs need to enhance their ecoP by adopting new technologies. Additionally, better management of their operational practices is recommended. It is finally evidenced that over the years WoCs moved to a better management of their resources used in the delivery of water to their customers contributing therefore positively to ecoP.

Contribution of variables to eco-productivity change and its components

The next step of our analysis aims to get a better understanding of what drove ecoP change in the water supply process. This involves examining the impact of each variable (energy costs, other costs, GHG emissions, volume of water delivered, and number of water connections) on ecoP. Figure 4 illustrates the contribution of each variable to the ecoP of English and Welsh water companies over the years. Our analysis concludes that, over time, GHG emissions and other costs have positively contributed to ecoP with annual average values of 3.22% and 0.91%, respectively. Conversely, energy costs, the volume of water delivered, and the number of water connected properties have negatively impacted ecoP. Their annual average values were –0.09%, –1.74% and –1.27%, respectively.

A remarkable finding from the analysis is that no single variable consistently contributed either positively or negatively to ecoP across all the years studied (2011–2018). This led to a modest overall improvement in ecoP over the years, as positive contributions were offset by the negative impacts of other variables. This highlights the importance of quantifying the impact of each variable on ecoP to better inform and support decision-making processes.

Variable impacts on ecoP showed notable shifts over the period. As depicted in Fig. 4, the efforts to reduce GHG emissions have become increasingly significant for the English and Welsh water industry, aligning with its commitment to achieve carbon neutrality by 2030[33]. Initially, from 2011 to 2013, GHG emissions had a negative impact on ecoP changes. However, from 2013 onwards, GHG emissions consistently contributed positively, reaching a peak increase of 10.4% in 2017–2018. Regarding other costs, their average annual contribution to ecoP from 2011 to 2018 was positive, at 0.91%. In contrast, energy costs had a negligible average annual negative contribution of –0.09%. Notably, during the last period evaluated

Fig. 5 | Contribution of each variable to eco-productivity change of English and Welsh water only companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.

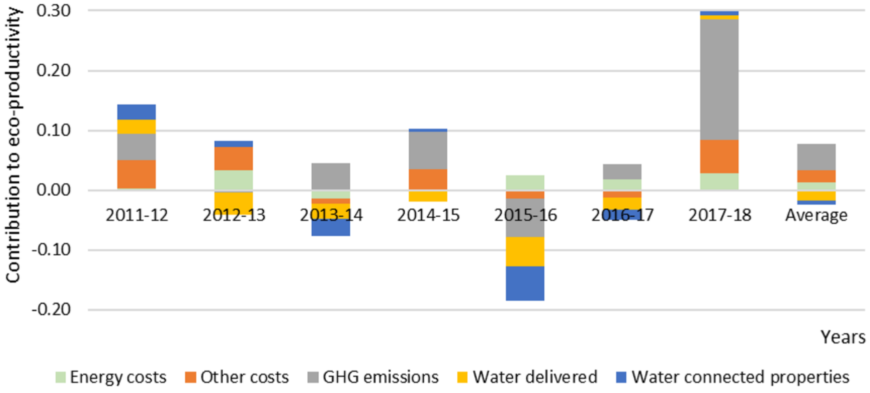
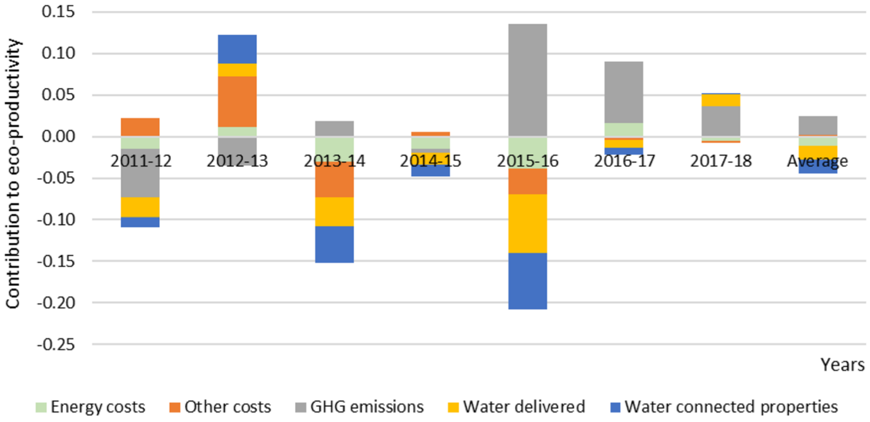


Fig. 6 | Contribution of each variable to eco-productivity change of English and Welsh water and sewerage companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.



(2016–2018), the industry's improvements in energy efficiency began contributing positively to ecoP. The volume of water delivered predominantly had a negative impact on ecoP from 2011 to 2017. It was only in the last year evaluated (2017–2018) that its contribution turned positive. In fact, water delivered had the most significant negative average annual impact on ecoP, at −1.74% from 2011 to 2018. This underscores the necessity for water utilities to enhance water resource efficiency. Water savings could be achieved through information campaigns that educate the public on more efficient water use and the installation of water-saving technologies in homes (Florez et al., 2019). Additionally, the deployment of smart water meters could promote more sustainable water consumption by customers and enable water companies to identify leaks, thus reducing water loss[39].

Figures 5 and 6 illustrate the contribution of each variable to ecoP change based on company type, i.e., WoCs and WaSCs. For WoCs, energy costs, other costs, and GHG emissions contributed positively to ecoP change, with annual average values of 1.34%, 2.00%, and 4.44%, respectively. In contrast, water delivered and water connected properties contributed negatively to ecoP, with average values of −1.70% and −0.80%, respectively. For WaSCs, other costs and GHG emissions also contributed positively to ecoP, with average annual values of 0.14% and 2.37%, respectively. However, energy costs, water delivered, and water connected properties negatively contributed to ecoP, with average annual values of −1.08%, −1.76%, and −1.60%, respectively.

The results indicate that both WaSCs and WoCs made considerable efforts to reduce GHG emissions over time, as this variable contributed most positively to ecoP change for both types of water companies. However, the evolution of GHG emissions did not follow the same trend for both types. For WaSCs, the positive trend in GHG emissions became significant from 2015 onwards, whereas in previous years (2013–2014), it was negative or slightly positive. In contrast, with the exception of 2012–2013 and 2015–2016, changes in GHG emissions from WoCs were positive in all years, contributing positively to ecoP. Regarding energy costs, the variable whose contribution differs the most among WaSCs and WoCs, it is noted that WaSCs experienced a positive contribution of energy costs to ecoP in the years 2012–2013 and 2016-17. In the remaining years, the contribution of energy costs to ecoP was negative, reaching a maximum negative value in 2015–2016 with −3.89%. By contrast, with the exception of 2013–2014, energy costs improved across the years for WoCs, contributing positively to ecoP. Thus, it is evident that reducing energy costs was particularly challenging for an average WaSC.

The results evidenced that although WasCs and WoCs are regulated according to the same approach, the managerial and operational strategies applied by both types of water companies differ. The divergent strategies of WaSCs and WoCs can be attributed to their distinct operational scopes. WaSCs are responsible for both water supply and wastewater services, necessitating a broader range of operational activities and infrastructure compared to WoCs, which focus solely on water supply. As a result, WaSCs may prioritize investments to reduce GHG emissions and energy costs in wastewater treatment technologies and infrastructure, while WoCs concentrate on improving water supply systems. Moreover, WaSCs face additional regulatory requirements related to wastewater management, which can impact their cost structures and investment needs. Conversely, WoCs might focus more on water conservation and supply resilience. Therefore, when setting targets, the regulator must consider these distinct operational contexts to ensure that the benchmarks are both relevant and achievable for each type of company.

The contribution of each variable to ecoTC, according to Eq. (9) is illustrated on Fig. 7 for the whole sample of assessed water companies and on Figs. 8 and 9 for WoCs and WaSCs, respectively. The negative average ecoTC for the entire period (−1.1% per year) was predominantly driven by the volume of water delivered, which exhibited an annual average decrease of −2.25%. Notably, it was only in the final period evaluated (2017–2018)

Fig. 7 | Contribution of each variable to eco-technical change of English and Welsh water companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.

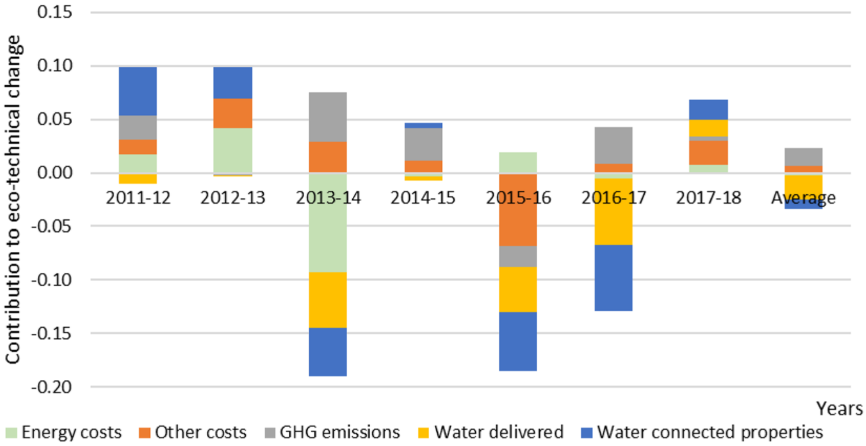


Fig. 8 | Contribution of each variable to eco-technical change of English and Welsh water only companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.

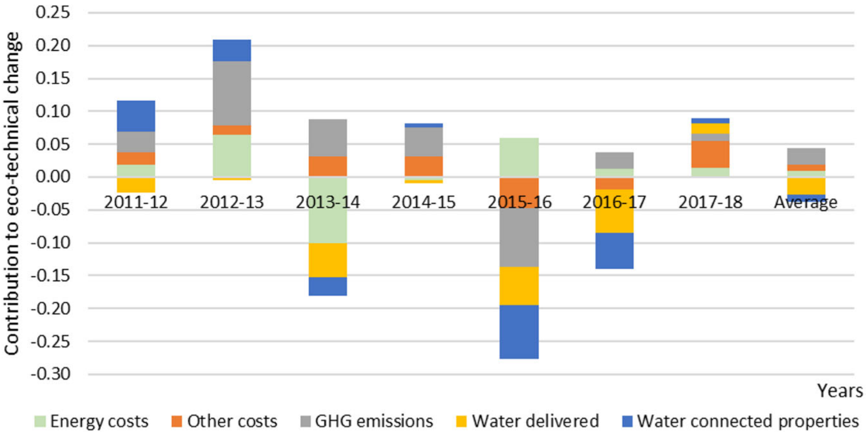
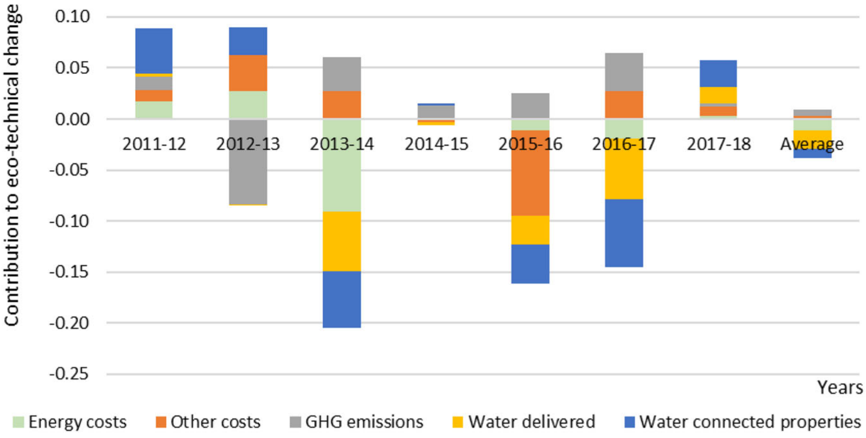


Fig. 9 | Contribution of each variable to eco-technical change of English and Welsh water and sewerage companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.



that this variable made a positive contribution to the ecoTC, suggesting a temporary or potentially emerging shift in water delivery dynamics. Conversely, GHG emissions emerged as the variable with the most significant positive contribution to ecoTC, averaging an increase of 1.65% annually. This positive trend underscores a critical focus on environmental performance, particularly in reducing carbon footprints, among English and Welsh water companies. The substantial positive contribution of GHG emissions to ecoTC indicates that technological advancements in recent years have been primarily aimed at mitigating environmental impacts.

These observations point to a strategic prioritization by water companies towards enhancing their environmental sustainability through technological improvements. The marked reduction in GHG emissions reflects efforts such as the adoption of energy-efficient technologies, implementation of renewable energy sources, and improvements in operational practices aimed at lowering carbon emissions. This focus aligns with broader environmental goals and regulatory pressures to reduce the carbon footprint and achieve sustainability targets.

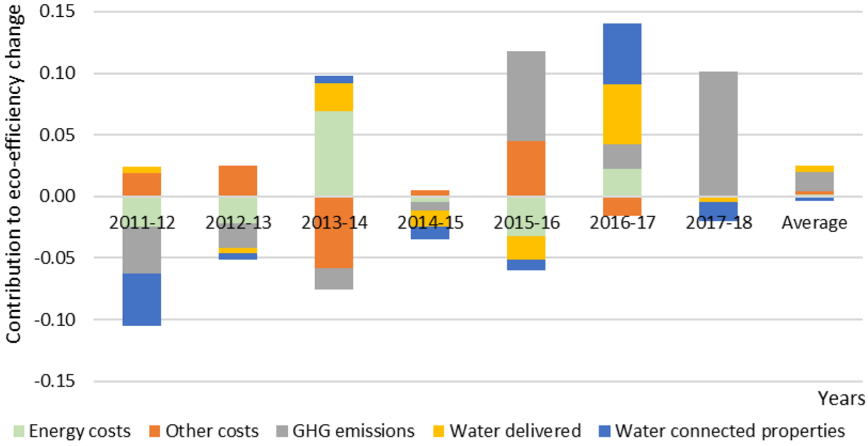


Fig. 10 | Contribution of each variable to eco-efficiency change of English and Welsh water companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.

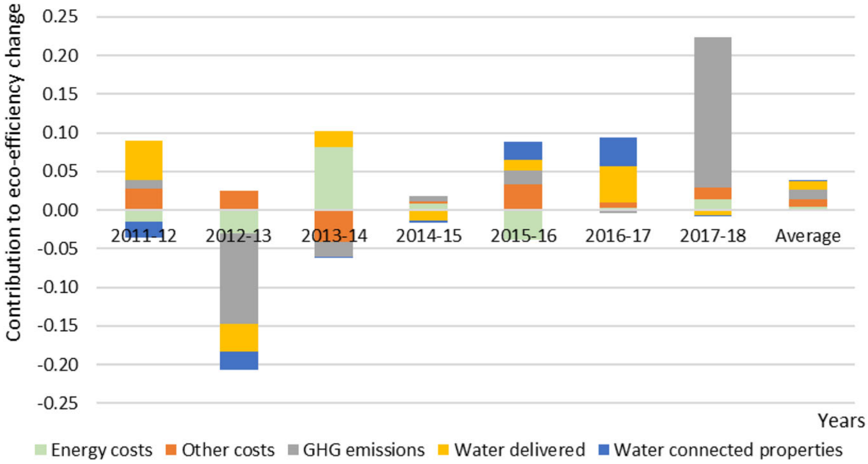


Fig. 11 | Contribution of each variable to eco-efficiency change of English and Welsh water only companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.

Analysis of the results based on company type reveals that, on average, WoCs (Fig. 8) demonstrated greater technological leadership than WaSCs (Fig. 9) during the study period. WoCs' adoption of best practice technologies facilitated control over their production costs and GHG emissions. Due to technical progress, WoCs experienced an annual reduction in energy costs and other costs by 0.9% and 1.0%, respectively. This reduction also positively impacted their GHG emissions, with an average annual improvement rate of 2.5% in ecoTC. In contrast, the rate of new technology adoption among WaSCs was less pronounced. It is evident that improvements in other costs and GHG emissions among WaSCs were only marginal. This could be attributed to the fact that WaSCs were less effective in developing technologies that could help manage energy costs effectively. Consequently, to enhance their eco-performance, WaSCs need to demonstrate more technical leadership and embrace more innovative solutions.

The impact of each input and output on the ecoEC of the assessed water companies is illustrated in Fig. 10. Unlike ecoTC, in the case of ecoEC, only the variable 'water connected properties' contributed negatively, with an annual average decrease of –0.38%. The contributions of the remaining variables were positive, with annual average increases of 0.14% for energy costs, 0.28% for other costs, 1.57% for GHG emissions, and 0.52% for water delivered. This analysis indicates that as in the case of ecoP change, where no consistent trends were observed across the variables, the contribution to ecoEC exhibited both positive and negative shifts, except for GHG emissions, which consistently contributed positively during the last three years evaluated. This pattern suggests that water companies in England and Wales have been actively developing and implementing strategies specifically aimed at reducing carbon emissions. However, it appears that there has been a lack of long-term planning concerning the other variables that contribute to ecoEC and, consequently, to overall ecoP.

The findings by company type show that for WoCs all variables contributed positively to ecoEC from 2011 to 2018 (Fig. 11). This indicates that WoCs have improved their performance in terms of production costs, GHG emissions, and water delivered. Notably, the contribution of GHG emissions was particularly significant during the last period evaluated (2017–2018), where it improved by 19.5% in just one year. This substantial increase was influenced by the 2016 commitment of the English and Welsh water industry to achieve carbon neutrality by 2030 (Ofwat, 2024). Conversely, WaSCs did not achieve considerable gains in efficiency regarding energy costs, other costs, and water connected properties (Fig. 12). Therefore, WaSCs could enhance their eco-performance by better managing production costs. Despite these challenges, the average contribution of GHG emissions for WaSCs was positive, averaging +1.77% per year, which supported the positive ecoEC of WaSCs from 2011 to 2018. This underscores the significant role that reducing GHG emissions has played in improving the eco-performance of water companies in England and Wales.

Environmental variables influencing eco-productivity change

To determine the influence of environmental variables related to the source and quality of raw water, as well as population density, on ecoP estimations, a regression tree method was employed. The results, displayed in Fig. 13, show that population density (PD), the percentage of water abstracted from boreholes (WB), and the number of treatment works required when water is abstracted from groundwater resources (TG) had significant impacts on ecoP (see Supplemental Fig. 1). Moving from left to right, it is concluding

Fig. 12 | Contribution of each variable to eco-efficiency change of English and Welsh water and sewerage companies. Colors of each bar are as follows: green color is energy costs, orange color is other costs, gray color is carbon emissions, yellow color is water delivered and blue color is water connected properties.

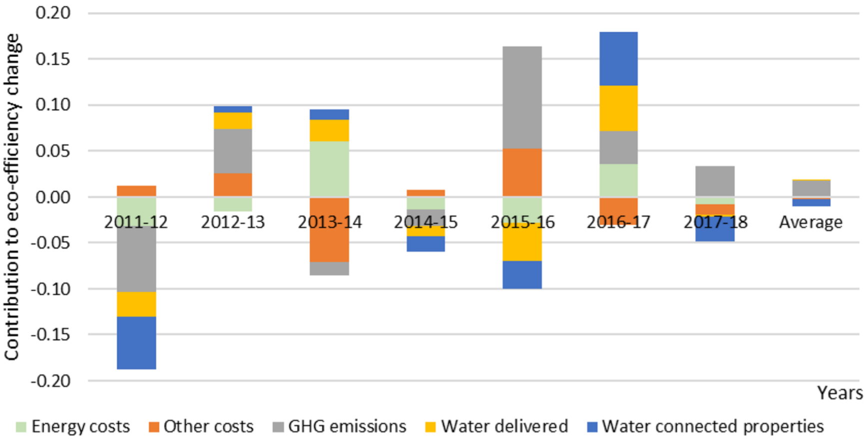
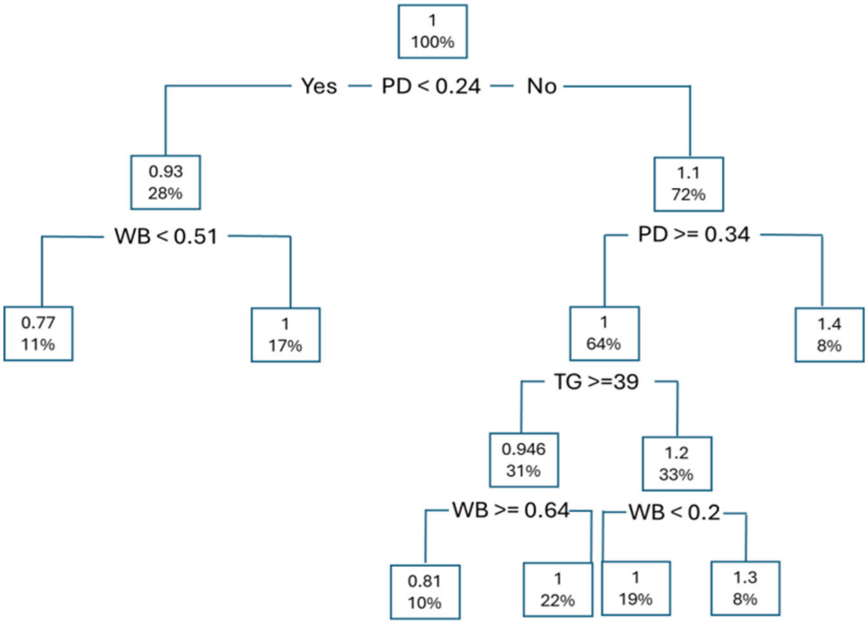


Fig. 13 | Regression tree analysis to identify the influence of environmental variables on eco-productivity change estimations. Estimations are based on population density (PD), water abstracted from boreholes (WB) and number of treatment works required when water is abstracted from groundwater resources (TG).



that if the PD is lower than 0.24 residents per km of water main then ecoP will be negatively impacting achieving a maximum value of 0.93. Lower levels of ecoP could be achieved if those areas receive less than half of their water from boreholes. However, higher levels of ecoP could be achieved if more than half of water is abstracted from boreholes. Thus, less densely populated areas could improve ecoP by abstracting water from boreholes if this source of raw water is available. In contrast, if population density is between 0.24 and 0.34 resident per km of main, then ecoP could reach the level of 1.4. This means that on average it might be less costly to provide water services to those densely populated areas. It is found that if PD is higher than 0.34 residents per km of water main, then more water needs to be abstracted from boreholes, i.e., more than 64% of available water. This pushes up the number of treatment works from groundwater resources to ensure that water is clean before it is supplied to customers. This process puts pressure on production costs and GHG emissions leading to a decline in ecoP, 0.81 on average. In contrast, lower levels of water abstracted from boreholes could require less treatment (less than 39 treatment works on average) which could lead to higher levels of ecoP, 1.3 on average.

The findings from our study offer valuable insights for policymakers and water managers. Firstly, our methodological approach enhances understanding of the water-energy-carbon nexus in the water system by quantifying the impact of each variable on the ecoP change of water companies. This allows water regulators and managers to assess the effectiveness of existing policies, e.g., those aimed at reducing GHG emissions, and to identify areas for improvement, such as energy costs. This analysis could be even more detailed if data were available for each stage of the drinking water supply process—i.e., abstraction, treatment, and distribution—or for the different types of equipment involved, such as pumps, filters, blowers, etc. Such detailed data would allow for a more specific assessment of performance and enable a deeper understanding of the specific contributions of each stage and piece of equipment to ecoP.

Our findings highlight that enhancing performance in the water sector requires more than just focused policies on water companies; educational campaigns aimed at reducing water demand are crucial for improving ecoP. This aspect underscores the importance of comprehensive strategies that include consumer behavior to effectively increase ecoP. Furthermore, the secondary stage of our analysis reveals that various environmental variables significantly influence the ecoP of water companies. Therefore, it is advisable for water regulators to avoid setting uniform ecoP targets for all water companies. Instead, targets should be tailored to account for specific environmental conditions affecting each company's ecoP. This tailored approach can lead to more effective and efficient management of resources within the water sector.

Methods

Eco-productivity and its drivers

To estimate the ecoP change of water companies and the contribution of each variable (input, desirable output and undesirable output), the WRDDM proposed by Fujii et al.[28], which is based on the directional distance function, is used. Assume that a water company, uses a set of inputs denoted as x_K to produce a set of desirable outputs denoted as y_L and a set of undesirable products denoted as b_M. Based on this, the following production technology can be defined:

$$PPT = \{(x, y, b) | x \text{ are used to produce } y, b\} \tag{1}$$

As it is shown in Fig. 14, the production technology represents the relationship between the use of inputs and the generation of outputs, which include both desirable outputs such as drinking water supplied, and undesirable outputs such as carbon emissions.

Equation 1 fulfils the properties of strong disposability for desirable outputs and inputs, and weak disposability of undesirable outputs. This framework is operationalized through directional distance functions. It is a particular representation of a multi-output, multi-input production technology which allows for the simultaneous expansion of desirable outputs and contraction of undesirable outputs and inputs[40,41]. The directional distance function is defined as follows:

$$\vec{D}(x, y, b) = \sup\{\beta: x - \beta g_x, y + \beta g_y, b - \beta g_b\} \tag{2}$$

where g_x, g_y, g_b are the directions in which inputs, desirable outputs and undesirable outputs are scaled, respectively.

Setting the directional vector as $g = (g_x, g_y, g_b) = (-x, y, -b)$ enables the simultaneous expansion of desirable outputs and contraction of inputs and undesirable outputs. Thus, the eco-inefficiency of any water company n can be estimated by measuring the distance between its current performance—considering its use of inputs and generation of outputs—and the efficient production frontier, which represents the performance of the best-performing water companies. In doing so, the following WRDDM was solved for each water company[28]:

$$\vec{D}(x_n, y_n, b_n; g) = \max\left(\frac{1}{K}\sum_{k=1}^{K}\beta_{kn} + \frac{1}{L}\sum_{l=1}^{L}\beta_{ln} + \frac{1}{M}\sum_{m=1}^{M}\beta_{mn}\right) \tag{3}$$

$$\begin{gathered}
s.t. \\
\sum_{j=1}^{J}\lambda_j y_{lj} \geq y_{\mathrm{ln}}(1 + \beta_{\mathrm{ln}}) \qquad l = 1, \ldots, L \\
\sum_{j=1}^{J}\lambda_j b_{mj} = b_{mn}(1 - \beta_{mn}) \qquad m = 1, \ldots, M \\
\sum_{j=1}^{J}\lambda_j x_{kj} \leq x_{kn}(1 - \beta_{kn}) \qquad k = 1, \ldots, K \\
\sum_{j=1}^{J}\lambda_j = 1 \\
\lambda_j \geq 0 \qquad j = 1, \ldots, J \\
\beta_{ln} \geq 0 \qquad \beta_{mn} \geq 0 \qquad \beta_{kn} \geq 0
\end{gathered}$$

where K, M, L denote the total number of inputs, undesirable outputs and desirable products, respectively; J is the total number of DMUs. Moreover, $\beta_k^n, \beta_m^n, \beta_l^n$ are the inefficiency scores related to inputs, undesirable outputs and desirable products, respectively. Furthermore, λ denote intensity variables that are used to construct the efficient frontier.

Inefficiency scores ($\beta_{kn}, \beta_{mn}, \beta_{ln}$) provide insights into the performance of each water company at a specific point in time. The next stage in the analysis involves integrating a temporal component to examine changes in performance over time, specifically, to estimate ecoP changes. This study employs the Luenberger Productivity Indicator for several reasons. Firstly, it is based on differences, allowing it to incorporate results for variables even when their values are close to zero[42]. Secondly, it accounts for undesirable outputs in the modeling analysis and is derived using directional distance functions[43]. Furthermore, it can be decomposed into other determinants such as ecoTC and ecoEC, thereby elucidating the impact of changes in each input and output on these determinants[44].

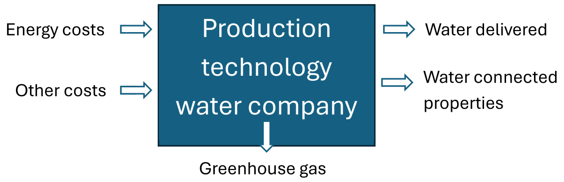


Fig. 14 | Representation of the relationship between inputs, desirable outputs and undesirable outputs though the production technology of the water company. Variables reported are those employed in the empirical application.

Using the inefficiency estimates of the WRDDM defined in model (3) changes in ecoP for any water company n between two time periods, t and $t + 1$, and its determinants ecoTC and ecoEC are estimated as follows:

$$\begin{aligned}
ecoP_t^{t+1} = \frac{1}{2}\Big\{&\vec{D}^{t+1}(x_n^t, y_n^t, b_n^t) - \vec{D}^{t+1}(x_n^{t+1}, y_n^{t+1}, b_n^{t+1}) \\
&+ \vec{D}^t(x_n^t, y_n^t, b_n^t) - \vec{D}^t(x_n^{t+1}, y_n^{t+1}, b_n^{t+1})\Big\}
\end{aligned} \tag{4}$$

$$\begin{aligned}
ecoTC_t^{t+1} = \frac{1}{2}\Big\{&\vec{D}^{t+1}(x_n^t, y_n^t, b_n^t) + \vec{D}^{t+1}(x_n^{t+1}, y_n^{t+1}, b_n^{t+1}) \\
&- \vec{D}^t(x_n^t, y_n^t, b_n^t) - \vec{D}^t(x_n^{t+1}, y_n^{t+1}, b_n^{t+1})\Big\}
\end{aligned} \tag{5}$$

$$ecoEC_t^{t+1} = \vec{D}^t(x_n^t, y_n^t, b_n^t) - \vec{D}^{t+1}(x_n^{t+1}, y_n^{t+1}, b_n^{t+1}) \tag{6}$$

$$ecoP_t^{t+1} = ecoTC_t^{t+1} + ecoEC_t^{t+1} \tag{7}$$

where $ecoP_t^{t+1}$, $ecoTC_t^{t+1}$ and $ecoEC_t^{t+1}$ represent ecoP change, ecoTC and ecoEC, respectively; $\vec{D}^t(x_n^t, y_n^t, b_n^t)$ denotes the inefficiency of any DMU n at year t based on the frontier curve at year t, whereas $\vec{D}^{t+1}(x_n^t, y_n^t, b_n^t)$ presents the inefficiency of any DMU n at year t based on the frontier curve at year $t + 1$. Essentially, Eqs. (4–6) involve estimating the directional distance function as defined in Eq. (3), taking into account the performance of water companies for each year evaluated. Supplemental material presents the mathematical models solved to estimate the directional distance functions.

EcoP and its components can exhibit both positive and negative values. A positive ecoP value ($ecoP_t^{t+1}$) indicates that the water company improved its performance between time period t and $t + 1$, while a negative value signifies a deterioration in performance. Regarding the drivers of eco-productivity, a positive ecoEC ($ecoEC_t^{t+1}$) reflects efficiency improvements over time, while a negative value implies a decline in efficiency. Similarly, a positive ecoTC ($ecoTC_t^{t+1}$) denotes technical progress within the industry, whereas a negative value indicates technical regress.

Alternatively to the decomposition of ecoP change illustrated in Eq. (7), it is possible to further decompose it and its components based on their contributions from inputs, desirable outputs, and undesirable outputs as detailed in Eqs. 8–10[45]:

$$ecoP_t^{t+1} = P_{t,x}^{t+1} + P_{t,y}^{t+1} + P_{t,b}^{t+1} \tag{8}$$

$$ecoTC_t^{t+1} = TC_{t,x}^{t+1} + TC_{t,y}^{t+1} + TC_{t,b}^{t+1} \tag{9}$$

Table 1 | Descriptive variables used to assess eco-productivity change of water companies in England and Wales (2011–2018)

Variables	Unit of measurement	Average	Std. Dev.	Minimum	Maximum
Energy costs*	£m /year	19.72	14.58	1.51	59.99
Other costs	£m /year	91.17	75.85	7.56	331.65
Greenhouse gas	tonCO$_{2e}$ /year	86,151	70,335	4542	275,900
Water delivered	m^3/year	717.13	554.13	56.17	2168.81
Water connected properties	000 s	1489.55	1118.13	122.64	3826.42
WR	%	34.0	25.0	0.0	83.0
WB	%	39.0	30.0	0.0	92.0
TS	nr	16.15	15.28	1.00	54.00
TG	nr	47.70	40.51	2.00	127.00
HT	%	93.0	5.0	81.0	100.0
PD	000 s/km	0.48	0.29	0.15	1.25

*Energy and other costs are expressed in 2018 prices.

$$ecoEC_t^{t+1} = EC_{t,x}^{t+1} + EC_{t,y}^{t+1} + EC_{t,b}^{t+1} \tag{10}$$

where $P_{t,x}^{t+1}$, $P_{t,y}^{t+1}$, and $P_{t,b}^{t+1}$ represent the contribution of inputs, desirable outputs and undesirable outputs, respectively, to ecoP change. Similarly, $TC_{t,x}^{t+1}$, $TC_{t,y}^{t+1}$, and $TC_{t,b}^{t+1}$ denote the contributions of inputs, desirable outputs, and undesirable outputs, respectively, to ecoTC. Moreover, $EC_{t,x}^{t+1}$, $EC_{t,y}^{t+1}$, and $EC_{t,b}^{t+1}$ detail the contributions of inputs, desirable outputs, and undesirable outputs, respectively, to ecoEC. For example, a positive value of $P_{t,x}^{t+1}$ suggests that changes in inputs have contributed positively to ecoP change. Conversely, a negative value of $P_{t,x}^{t+1}$ implies an increase in inputs usage over time, leading to a decrease in ecoP. This interpretation is similarly applied to all components defined on Eqs. (8–10).

Environmental variables influencing eco-productivity

The next step in the analysis involves determining if there are environmental variables that might impact the ecoP change of water companies. For this purpose, a regression tree method is utilized, which predicts changes in ecoP (outcome variable) based on a set of operating characteristics (environmental variables)[46]. Regression trees are particularly useful for visualizing interactions between different variables in the water supply process and analyzing how these variables might affect ecoP[24].

The regression tree approach partitions the dataset into smaller subsets (or regions) based on a set of explanatory variables, which can be either categorical or continuous[47]. According to James et al.[48], constructing a regression tree involves a two-step approach. The first step divides the total sample into several distinct, non-overlapping regions[49], and the second step calculates the average predicted value of the response variable—in this case, ecoP—based on the observations within each region.

Data sample and variables selection

The English and Welsh water industry operates under private ownership, with the economic and environmental performance overseen by Ofwat[50]. Every five years, water companies are required to submit their business plans to Ofwat, which then approves their future revenue allowances during the price review process.

The selection of variables to assess ecoP change and its components was aligned with the objectives of this study and in consistency with previous research on this topic[15,51,52]. Two inputs were utilized. The first input was defined as the annual energy expenditure of water services, measured in millions of £. The second input, termed other expenditure, was measured in millions of £ per year and calculated as the difference between total operating expenses and energy expenditure. GHG emissions associated with the abstraction, production, and supply of drinking water were included as an undesirable output. These emissions, measured in tons of CO$_{2e}$ per year, are based on the United Kingdom Government Environmental Reporting Guidelines[53]. The carbon emissions regulated by Ofwat in the provision of drinking water are considered across three categories: (i) Scope 1: GHG emissions from transportation that is owned or leased, as well as emissions from the companies' own fossil fuel use; (ii) Scope 2: GHG emissions from grid electricity used for pumping, treating, and distributing water, as well as electricity used in owned buildings; and (iii) Scope 3: GHG emissions from contractors and outsourced services, and business-associated transportation, including travel on public transport or in private vehicles[54]. Additionally, two desirable outputs were employed in this study. The first was the volume of water delivered, measured in megalitres per year. The second desirable output was the number of water-connected properties, quantified in thousands per year.

The selection of environmental variables that might influence ecoP changes of water companies was based on data availability and insights from previous studies on the English and Welsh water industry[18,24,50]. The first two variables relate to the main source of raw water used to produce drinking water: (i) the percentage of water abstracted from reservoirs (WR) and (ii) the percentage of water abstracted from boreholes (WB). To assess the impact of raw water quality on ecoP change, three variables were considered: (i) the number of treatment works required for water abstracted from surface sources (TS), (ii) the number of treatment works required for water abstracted from groundwater sources (TG), and (iii) the percentage of raw water undergoing high levels of treatment (HT). Additionally, population density (PD), defined as the population divided by the length of water mains, was included as the last environmental variable.

All data for this study was sourced from the OFWAT webpage. Specifically, it has been used data from the "Service delivery reports", "FCA performance scorecard", "Discover water dashboard", "Reports from 2009, 2014 and 2019 price reviews" and "Open data in the water industry". The main descriptive statistics of the variables used in the sample are presented in Table 1.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Code availability

The codes generated and/or used during the current study are available from the corresponding author upon reasonable request.

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Author contributions

Alexandros Maziotis: Methodology; Sofware; Writing—Original Draft. Ramón Sala-Garrido: Methodology; Sofware. Manuel Mocholi-Arce: Writing—Review & Editing. María Molinos-Senante: Conceptualization; Visualization; Writing—Review & Editing.

Competing interests

The authors declare no competing interests.

Additional information

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