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Full Length Article

An initial assessment of water security in Europe using a DEA approach

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A B S T R A C T

The global freshwater crisis has prompted the development of innovative methods to assess the sustainability of water resources around the world. In the last decade, the concept of water sustainability has evolved, giving rise to a more advanced measure of societies' capacity to safeguard water resources; namely, water security. In this paper, we calculate a composite index to assess water security through the application of a DEA approach. The proposed model is used to aggregate nine indicators relating to the four dimensions of water security: state of the water environment; human health and wellbeing; sustainability of livelihoods; and the stability, functions and responsibility of societies. The model was applied to 15 European countries. Benchmarking results of the analysed countries show that Denmark, the United Kingdom and Finland hold the best positions in the ranking. The findings thus indicate that these countries show excellent performance in water security relative to the other countries under study.

Introduction

The global water crisis that people are currently facing jeopardizes the availability of enough quality water to ensure their well-being, health and economic development. Only 2.5% of the world's water is freshwater available for human consumption, while global water consumption registers continuous growth of 1% per year (de Castro-Pardo et al., 2021). This small proportion of freshwater is the driving force of human health, the global economy and the wellbeing of society in the broadest sense (Pérez-Zabaleta et al., 2020). Unsustainable management of water resources, with rising withdrawal rates, has severely compromised the global availability of freshwater. For example, by 2014, the average availability of renewable freshwater worldwide had recorded a sharp fall of around 40% since the 1970s (The Economist Intelligence Unit Limited, 2019). On the other hand, the problem is exacerbated by an unequal distribution of freshwater resources around the world and their marked seasonality.

The scarcity of water as a resource and the complexity associated with the management of large watercourses have historically led to severe conflicts about how they are managed. These conflicts can block decision-making processes and even spark armed conflicts between countries, especially when the management involves multiple jurisdictions or countries (Chellaney, 2013). Although there are international regulations governing the use of transboundary watercourses and international waters, at the operational level, stakeholders must also be involved in different processes related to their ongoing maintenance, implementation and evaluation (Suski et al., 2007), which often leads to clashes.

Against this backdrop, the concept of water security becomes particularly relevant. According to UN Water (2013) "Water security is the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability".

Water security has its roots in the post-war diplomacy of the 1940s aimed at redrawing the political boundaries of former colonial empires (Gleick, 1993). Interest in water security has grown since the United Nations Ministerial Declaration of The Hague on Water Security in the 21st Century was issued at the World Water Forum in 2000 (United Nations, 2000). Since then, there has been a proliferation of definitions, leading to convergence and generating confusion about the concept itself and ways of measuring and managing it (Grey et al., 2013). The Declaration recognized the importance of managing risks and using objectives and strategies to ensure the achievement of goals such as ensuring that all people have access to

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sufficient quantities of safe, affordable water needed to lead healthy, productive lives, and that the most vulnerable groups are protected from the risks of water-related hazards. In addition, it emphasizes the growing interest in water security indicators (WSI) to carry out proper monitoring and to generate the information needed to improve water management decision-making.

Although developing strategies and regulations is undoubtedly the first step to implementing actions that mitigate the global water crisis, it is also essential to objectively assess the progress made by these international commitments in order to measure their impact and effectiveness, and to get an objective picture of countries' degree of compliance (Munda, 2010).

In this regard, composite indicators are especially useful for the implementation, monitoring and improvement of public policies (Fernández et al., 2020) as they provide more information than key indicators and also enable effective communication. Since the beginning of the twentieth century, concern about monitoring sustainable development policies has led to the development of several aggregate indices to measure water sustainability (Juwana et al., 2012) and some specifically aimed at measuring water security, such as those proposed by Assefa et al. (2019), Shrestha et al. (2018) and Jensen and Wu (2018) in urban environments or Zhou et al. (2021) in rural areas.

One of the methods most frequently employed to construct composite indicators when there is no known information available regarding weights is Data Envelopment Analysis (DEA) applied using the Benefit-of-the-Doubt (BoD) approach. DEA is often used to analyse best practices or efficiency in production or the delivery of a service (Phucharoen and Sangkaew, 2020). The main disadvantage of this method is that without setting constraints, the weight is given by an indicator in which the unit under analysis performs the best (Cherchye et al., 2007). As such, the results can be influenced by the fact that decision-making units that perform very well in a single indicator can occupy the best positions for the overall indicator.

The aim of this study is to present the application of a BoD-DEA model to measure the water security of 15 European countries by means of a benchmarking optimization approach.

Section 2 describes the selected indicators and the method, while Section 3 presents and discusses the results of the application. Lastly, Section 4 sets out the conclusions.

Material and methods

Indicators and data

The definition of water security comprises four key dimensions (Marttunen et al., 2019): the sustainability of livelihoods; human health and wellbeing; the state of the water environment; and the stability, functions and responsibility of society. Hoekstra et al. (2018) also identified these four elements in the literature, which they summarized as sustainability, welfare, equity, and water-related risks.

Following these approaches, a total of nine indicators were selected for this study, grouped into four dimensions (Table 1).

Dimension 1: Sustainability of livelihoods

1.1. Renewable freshwater resources per inhabitant. This is a “more is better” type indicator (+) and represents the availability of water per capita.

1.2. Water exploitation index. This is a “less is better” type indicator (-). This index shows the mean annual total demand for freshwater divided by the long-term average freshwater resources. It gives an indication of how the total water demand puts pressure on the water resource (Environmental European Agency, 2021).

Dimension 2: Human health and wellbeing

2.1. Proportion of population using safely managed drinking water services. This indicator is a “more is better” type indicator (+).

2.2. Population connected to at least secondary waste water treatment. This is also a “more is better” type indicator (+).

Dimension 3: State of the water environment

3.1.Estimated soil loss due to water erosion by land cover type. This indicator is a “less is better” type indicator (-).

3.2. Average proportion of Freshwater Key Biodiversity Areas (KBAs) covered by protected areas. This indicator is a “more is better” type indicator (+) and represents the percentage of protected Freshwater KBAs (IUCN 2012).

Dimension 4: Stability, functions and responsibility of societies

4.1. Corruption Perception Index (CPI). This indicator is a “less is better” type indicator (-). It assesses the perceived levels of public sector corruption, as identified by expert assessments and opinion surveys. The CPI generally defines corruption as an “abuse of entrusted power for private gain” (Transparency International, 2021).

4.2. Environmental Performance Index for water resources. This indicator is a “more is better” type indicator (+). It provides quantitative metrics for the assessment of a country's environmental performance regarding different policy categories relative to clearly defined targets (Environmental Performance Index, 2021).

4.3. Water productivity. This indicator is a “more is better” type indicator (+). Water productivity indicates how much economic output is produced per cubic metre of freshwater abstracted and measures the efficiency of water use. Total freshwater abstraction includes water removed from any freshwater source, either permanently or temporarily. Mine water and drainage water as well as water abstractions from precipitation are included, whereas water used for hydroelectricity generation (in situ use) is excluded (Eurostat, 2021).

All indicators were normalized using a max-min or min-max scaling method. The (+) type indicators were calculated by first subtracting the minimum value and then dividing by the difference between the maximum value and the minimum value. The (-) type indicators were calculated by first subtracting the maximum value and then dividing by the difference between the minimum value and the maximum value. By so doing, all indicators took a value between 0 and 1, where the maximum value was 1 and the minimum value 0.

The model

DEA has been used to construct composite indicators relating to natural resources (Hatefi and Torabi, 2010; Juwana et al., 2012).

The construction of composite indicators requires a multidimensional approach allowing different criteria to be aggregated in a structured way. In this respect, Multi-Criteria Analysis (MCA) techniques are particularly suitable (El Gibari et al., 2019) for measuring complex phenomena such as water security. In this paper, we present a model designed using a BoD-MCA approach to measure water security in 15 European countries in relation to 9 indicators.

The origins of the BoD approach lie in the application of DEA in a setting of imprecise data. DEA is a linear programming technique that evaluates a set of homogeneous production units, using input variables and output variables in an uncertain environment, where the weights associated with these variables are not known nor is the functional form of the relationship between these variables. A great many studies have already successfully applied this approach to construct composite indicators, including Cherchye et al. (2011), Karagiannis (2017) and Guaita et al. (2020). The only difference with respect to traditional DEA models is that only the output variables are set, taking a single dummy variable with a value equal to 1 as the input for each unit of analysis. The BoD model positions the performance of a decision-making unit in relation to the rest of the decision-making units and assigns the highest weights to the first indicators and the lowest to the second, so that the model selects the most favourable set of weights for each unit of analysis.

Table 1
Description of indicators, unit, year of most recent data, type and source, by dimension. (+) type indicators are "more is better" indicators and (-) type are "less is better" indicators.

Dimensions	Indicators and units	Year (last available data)	Type	Source
1. Sustainability of livelihoods	1.1.Renewable freshwater resources per inhabitant	2017	+	Eurostat (2021)
	1.2. Water exploitation index (%)	2017	-	European Environment Agency (2021)
2. Human health and wellbeing	2.1.Proportion of population using safely managed drinking water services (%)	2017	+	SDG (2021)
	2.2.Population connected to at least secondary waste water treatment (%)	2017	+	Eurostat (2021)
3. State of the water environment	3.1.Estimated soil loss by water erosion by land cover type (tonnes per hectare)	2016	-	European Commission - Joint Research Centre (JRC)
	3.2. Average proportion of Freshwater Key Biodiversity Areas (KBAs) covered by protected areas (%)	2019	+	SDG (2021)
4. Stability, functions and responsability of societies	4.1. Corruption Perception Index (score: worst 0–100 best)	2019	-	Transparency International (2021)
	4.2. Environmental performance index (water resources) (score: worst 0-100 best)	2020	+	EPI (2020)
	4.3.. Water productivity (Euro per cubic metre (Euro: chain-linked volumes, reference year 2010, at 2010 exchange rates))	2017	+	Eurostat (2021)

The model proposed here to measure water security is the following:

$$WSI_c = \max \sum_{i=1}^{m} w_{c,i} I_{c,i} \quad (1)$$

s.t.

$$\sum_{i=1}^{m} w_{c,i} I_{j,i \le 1} \quad (2)$$

$$w_{c,i \ge 0} \quad (3)$$

where j=1,2,.….,n and i=1,2,.…….,m, WSI_c= is the water security index of decision-making unit c, $w_{c,i}$ is the weight of decision-making unit c regarding indicator i, $I_{c,i}$ is the indicator i for each decision-making unit c, $I_{j,i}$ is the indicator i for each country j.

The results yielded by the model are compared to those from a method based on the unweighted average (UA), which is the most widely-used method for aggregating indicators (Eq. (4)).

$$xc, i = \sum_{i=1}^{m} w_{c,i} I_{j,i} \quad (4)$$

where $w_{c,i}$ represents equal weights for all the decision-making units.

Results and discussion

The normalized results of the indicators for each country analysed are shown in Table 2. The best scores for per capita availability of water resources are registered by Finland, which stands a long way ahead of the rest of the countries. With regard to the degree of exploitation of water, Finland still has the best scores, but followed this time by Denmark and the United Kingdom. For the indicators associated with human health, the top scoring countries lie closer together, with Greece, the Netherlands and the United Kingdom standing out in terms of access to drinking water, and the United Kingdom, the Netherlands and Luxembourg in terms of access to water treatment systems. The Netherlands, Finland and Denmark are the countries least afflicted by water erosion, while the countries with the most extensive area of protected freshwater KBAs are Ireland and the Netherlands. Denmark and Finland present the best scores for control of corruption and environmental performance in terms of water resources, while Luxembourg's scores for water productivity are far better than those of other countries.

It should be noted that the scaling method used emphasizes the distances between the best value and the worst value. This means that not all low normalized scores imply low indicator values. These scores only represent the distance of a country's score from that of the highest scoring country. For example, in the application presented in this study, there are some indicators which show very high scores registered by all countries. This is the case with the indicators for access to drinking water (2.1.), where all the countries analysed have percentages of the population with access to drinking water of between 95.04% and 100% .

The results of the WSI—that is, the aggregate results provided by the BoD-DEA model—reflect the highest possible values for all the countries, since the model selects the most favorable set of weights for each unit of analysis/country.The model has to be run for each decision-making unit; in this case, for each country. As such, the model has to be run 15 times in total. This model is very flexible when selecting the optimal weights, as it only has to comply with two constraints: constraint (2), which normalizes the weights, and constraint (3), which determines that the composite indicator is an increasing function of the indicators, such that an improvement in one of the indicators will always mean an improvement in the final WSI score (Fig. 1)

Applying the DEA approach, the aggregate results show that, in terms of benchmarking, the countries with the best water security results are Denmark, the United Kingdom and Finland. This means that from an optimization perspective, the aggregate results are excellent compared to the other countries analysed. In particular, Denmark registers the best score with a CI=1.0000.

If we compare the results provided by the proposed model and those provided by an additive aggregation approach with UA, it can be seen that only the United Kingdom (2nd) and Spain (13th) hold the same positions in the rankings, with the smallest differences seen in the countries ranked in the lowest positions, Italy and Portugal. Table 3

The application of the DEA model is appropriate in cases where there is no agreement as to the weights that should be assigned to each indicator. However, one of its main limitations is that it allows zero weights to be assigned to some indicators in the calculation of the CI.

On the other hand, the UA aggregation method is easier to apply. That said, it is a less accurate method, since it does not identify optimal indicators but rather distributes the values of all the indicators equally, regardless of their efficiency.

Table 2
Normalized indicators scores.

			2.1.	2.2.	3.1.	3.2.	4.1.	4.2.	4.3.
Belgium	0.0481	0.8271	0.9032	0.5782	0.8785	0.9106	0.6923	0.2867	0.0000
Czechia	0.0219	0.5119	0.5729	0.5619	0.7850	0.8958	0.2051	0.1289	0.1048
Denmark	0.0075	0.9773	0.3417	0.8218	0.9813	0.8899	1.0000	1.0000	0.2865
Finland	1.0000	1.0000	0.9260	0.6287	0.9907	0.5952	0.9744	1.0000	0.0256
France	0.0690	0.8573	0.5673	0.5000	0.8131	0.6676	0.5385	0.7333	0.0737
Germany	0.0332	0.8749	0.9597	0.9002	0.8598	0.7200	0.8205	0.9333	0.1076
Greece	0.2484	0.0000	1.0000	0.8366	0.5701	0.8163	0.0000	0.5933	0.0160
Ireland	0.4456	0.9389	0.4603	0.0384	0.9439	1.0000	0.6667	0.7711	0.2015
Italy	0.0971	0.6138	0.0000	0.0000	0.0000	0.7743	0.1282	0.0844	0.0319
Luxembourg	0.0919	0.9404	0.9445	0.9257	0.7103	0.0000	0.8205	0.9667	1.0000
Netherlands	0.1605	0.9087	0.9901	0.9876	1.0000	0.9971	0.8718	1.0000	0.0811
Poland	0.0324	0.8385	0.8299	0.3441	0.8879	0.8802	0.5128	0.1311	0.0386
Portugal	0.0347	0.6889	0.0549	0.6198	0.7383	0.4375	0.3590	0.0000	0.0341
Spain	0.0000	0.4040	0.6858	0.6688	0.5981	0.1835	0.3590	0.8111	0.0319
United Kingdom	0.0398	0.9966	0.9977	1.0000	0.8785	0.8377	0.7436	0.9667	0.2573

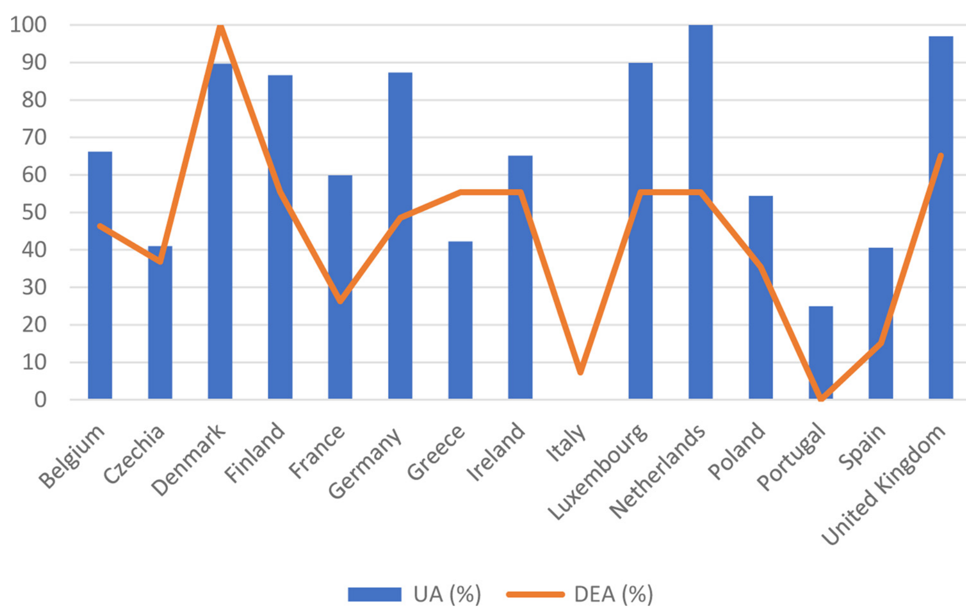

Fig. 1. DEA and UA scores (%).

Table 3
Normalized scores and ranking of DEA and UA aggregations.

	RANK DEA	RANK UA	NORMALIZED SCORES DEA (%)	NORMALIZED SCORES UA (%)
Belgium	9	7	46.38	66.18
Czechia	10	12	36.81	41.00
Denmark	1	4	100.00	89.66
Finland	3	6	55.44	86.63
France	12	9	26.33	59.92
Germany	8	5	48.57	87.31
Greece	6	11	55.41	42.27
Ireland	7	8	55.38	65.11
Italy	14	15	7.32	0.00
Luxembourg	5	3	55.41	89.85
Netherlands	4	1	55.42	100.00
Poland	11	10	35.40	54.39
Portugal	15	14	0.00	24.98
Spain	13	13	15.16	40.54
United Kingdom	2	2	65.13	96.96

Finally, these results should be interpreted with some caution. Both the normalization method and the benchmarking approach used in this study place the emphasis on the distances between the analysed countries' scores and those of the country with the best score. This means that countries in the lowest positions in the ranking may not necessarily have obtained low scores in the individual indicators. They are simply at a greater distance from the best-performing country's score.

The most up-to-date data were used for the analysis, despite the fact that the indicators refer to the 2016-2020 period. When interpreting results, the above should also be taken into consideration.

Conclusions

The BoD-DEA model presented in this paper has yielded a WSI that represents, in terms of benchmarking, the capacity of the analysed countries to sustainably safeguard their water resources, ensuring a sufficient quality and quantity of water to ensure the wellbeing of their inhabitants.

The countries with the best results in terms of water security compared to the rest of the countries analysed are Denmark, the United Kingdom and Finland.

The main advantage of the DEA approach is that it turns the focus on excellence and enables the construction of indicators that highlight the countries presenting the best results in all the elements analysed, relative to the rest of the countries. For this reason, the fact that some countries have low scores does not necessarily imply poor individual results.

The results of the application presented should be interpreted with caution due to the small number of indicators used and the benchmarking approach employed. It should also be taken into account that the results may change if new countries or new indicators are incorporated into the analysis.

Bearing these provisions in mind, the DEA approach can be a powerful methodological tool to improve decision-making processes and to monitor public policies related to international water management.

It would be interesting to continue working on the development of new, more complex BoD-DEA models, as well as to propose applications for measuring water security that include a larger set of indicators and countries from different regions of the world.

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