Ecological Indicators xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

A global Water Quality Index and hot-deck imputation of missing data☆

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ARTICLE INFO

Keywords:
Water Quality Index
Distance-to-target
Hot-deck imputation
Environmental Performance Index

ABSTRACT

Water is an essential resource for life on Earth and available freshwater resources are emerging as a limiting factor not only in quantity but also in quality for human development and ecological stability in a growing number of locations. Water quality is a significant criterion in matching water demand and supply. Securing adequate freshwater quality for both human and ecological needs is thus an important aspect of integrated environmental management and sustainable development. The 2008 Environmental Performance Index (EPI) published by the Yale Center for Environmental Law and Policy (YCELP) and the Center for International Earth Science Information Network (CIESIN) at Columbia University includes a Water Quality Index (WATQI). The WATQI provides a first global effort at reporting and estimating water quality on the basis of five commonly reported quality parameters: dissolved oxygen, electrical conductivity, pH value, and total nitrogen and phosphorus concentrations. This paper explains the motivation and methodology of the EPI WATQI and demonstrates how hot-deck imputation of missing values can expand its geographical coverage and better inform decision-makers on the types and extents of water quality problems in the context of limited globally comparable water quality monitoring data.

1. Introduction

Water is essential for all life and human activity and access to freshwater in sufficient amounts and of suitable quality is a precondition to achieving sustainable development. It is therefore at the heart of many international policy objectives, including the United Nations Millennium Development Goals (MDGs) (UN GA, 2000). The eight MDGs range from halving poverty to ensuring environmental sustainability and water quality management contributes both directly and indirectly to achieving all eight MDGs, because the goods and services that aquatic resources provide to people are fundamental to peace, security and prosperity (UNEP GEMS/Water, 2006).

The amount of available freshwater resources is estimated to be 43,750 km^3 per year (FAO, 2003), which far exceeds the joint requirements of households, industry, and agriculture. But resources are very unevenly distributed on a geographic and per capita basis.[1] In addition, water quality is threatened in many parts of the world by industrial discharges, agricultural run-off and irrigation, and municipal water pollution from homes and businesses (FAO, 2003).

Despite global economic and technological advances, an estimated 1.1 billion people – one sixth of the world population – do not have access to an improved source of drinking water (WHO, 2008). At the same time, empirical and theoretical evidence shows that investments to improve water quality generate multiple economic, social, and environmental benefits. For example, achieving the MDG targets for access to improved, cleaner and healthier water and sanitation facilities is estimated to result in 470 thousand fewer deaths due to water-related illnesses, lower health care costs, higher economic productivity through 320 million additional working days, fewer days of missed school for children, and total estimated economic returns on investment ranging from $3 to $34 for every dollar spent (WHO, 2008).

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[1] For instance, on a continental scale North America has the largest share (45%) of the world's freshwater resources while Africa has access to only 9%. Considering population size in addition to geographical location, the distribution of freshwater is even more skewed with availabilities of 24,000 m^3/year/capita in America but only 3400 m^3/year/capita in Asia. *Source*: FAO (2003).

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doi:10.1016/j.ecolind.2011.04.023

Ecologically, the maintenance of good quality water is essential to the protection of aquatic and terrestrial life and is directly linked to maintaining biodiversity. Rising water demands for expanding agricultural and industrial production coupled with increasing domestic needs from a growing world population has led to extensive modifications of inland waters (UNEP GEMS/Water, 2006). These modifications changed and continue to change the ecological landscape by reducing natural habitats, causing water pollution, introducing invasive species and manipulating water flows through the construction of dams and levees. The estimated loss in biodiversity associated with these modifications is so significant that the Convention on Biological Diversity described inland waters as one of the most threatened ecosystem types of all and that biodiversity of freshwater ecosystems is declining faster than for any other biome (Revenga and Kura, 2003).

The importance of water quality for human and ecological health and economic development is reflected in a number of water quality indices (WQI), employing various mathematical and statistical methods, that have been proposed over the past four decades, some of which have been implemented by water management and environmental agencies and are aiding decision-makers in water resource management, public health, and ecosystem protection (Abbasi, 2007; Cude, 2002a; Dinius, 1987; Haire et al., 1991; Hallock, 2002; Harkins, 1974; Horton, 1965; Inhaber, 1974; Kung et al., 1992; Landwehr, 1976b; Nagels et al., 2001; Parparov et al., 2006; Said et al., 2004; Schaeffer and Konanur, 1977; Stoner, 1978; Walski and Parker, 1974; Zoeteman, 1973). Despite the attention that water quality indices have received in the scientific and practitioners' literature, no single widely accepted method has emerged and furthermore, all currently used indices are restricted in their applicability and scope. In contrast to mainstream macro-economic indices such as GDP, there is as of yet no globally comparable index of freshwater quality.

This paper describes a first attempt to create a globally comparable freshwater quality index, henceforth termed WATQI, which was developed as an indicator for the 2008 Environmental Performance Index (EPI), a project of the Yale Center for Environmental Law and Policy, the Center for International Earth Science Information Network (CIESIN) and the World Economic Forum.[2] It discusses the challenges of defining and measuring water quality, with emphasis on the limited availability of global data, explains the rationale and method of the proposed WATQI, and discusses its utility and robustness as a policy tool.

The remainder of the paper is structured as follows. In Section 2 the concept of water quality is defined, measurement challenges highlighted and the theory and data basis for the WATQI are explained. Section 3 presents the results of the first global WATQI. The limitations but also opportunities and steps to further improve global water quality measurement are discussed in Section 4.

2. Data and methods

2.1. Defining water quality

The monitoring of water quality on a global basis is essential for human well-being as well as for ecological vitality. Identification of the causes of declining water quality and their geographical location is necessary for halting deterioration and implementing strategies for its improvement. However, the goal to manage water quality effectively requires a measurable definition of what constitutes water quality and how it translates into commonly used water quality classes such as "excellent", "good", or "unsuitable".

Water quality depends on the source, location, and the intended uses of the water. There are many different physical, biological, and chemical parameters as well as water quality criteria (standards) that can be used to measure water quality and, therefore, there is no single right answer to the question of 'what is water quality' (UNEP GEMS/Water, 2006). Water quality may be assessed in terms of, among others, 'quality for life' (e.g., the quality of water needed for drinking water), 'quality for food production' (e.g., the quality of water needed to sustain agricultural activities), or 'quality for nature' (e.g., the quality of water needed to support a thriving and diverse fauna and flora in a region) and the selection of parameters used to assess the quality of water depends largely on the intended use of the body of water. Thus, just as there are many reasons for monitoring water quality, there are many possibilities to define water quality and hence select water quality parameters, standards, and evaluation protocols.

Measuring water quality needs to take into account current ecological status with a management view towards achieving "good ecological status", as done, for example, in the European Union's Water Framework Directive (COM, 2000) within the context of locally determined conditions. For example, what constitutes 'ecologically healthy' levels of dissolved oxygen – an important indicator for the viability of the water source to support aerobic aquatic life – depends on factors such as the type of water body and its average temperature. Other aspects include local topography, soil and climatic conditions, historical land use, and many more. Thus, any search for a globally comparable and useful Water Quality Index needs to take into account that there is no single set of water quality parameter values that summarizes and defines all possible definitions of a healthy freshwater source.

2.2. Developing a global country-level Water Quality Index

The relevance of water quality in areas of public health, economic, social, and environmental policy provides the justification for monitoring and assessing water quality. A suitably designed and managed monitoring network, be it at the river, watershed/basin, community, or national level, can deliver the information and context required by water resource managers, public/private water utilities, and policy-makers to:

- identify water quality problems in time and space,
- determine priority areas in water quality and resource management, e.g., the reduction of eutrophication-causing effluents from agriculture into surface water,
- compare water quality at different locations and/or points in time,
- allocate funds and resources more effectively and efficiently to ensure water quality satisfies the requirements dictated by its designated uses,
- enforce water quality standards and regulations,
- inform the public about the status and trends in water quality,
- predict if and how changes in water management are likely to affect water quality, e.g., as a result of land use changes,
- formulate efficient and effective water resource management strategies, and
- supply input to scientific research into the determinants of water quality.

Yet, water monitoring networks in many countries are insufficient, badly designed, underfunded, defunct, or otherwise impaired to generate the information needed to effectively monitor and manage water quality. Globally, the UNEP GEMS/Water Programme is the only international program collecting global scientific informa-

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[2] A subsequent Water Quality Index was included in the 2010 EPI with a slightly refined methodology. For details visit http://www.ciesin.columbia.edu/repository/epi/data/2010EPI_metadata.pdf.

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tion on the status of surface and groundwater but participation in its country-level data collection and reporting activities is voluntary and countries can change or discontinue their reporting activities at any time. UNEP GEMS/Water collects a broad range of water quality parameters in conjunction with additional physical, topographical, and contextual information about the waterbodies, but to date there is no globally comparable and timely Water Quality Index for comparing water quality at the country level.

We, therefore, aimed to fill this gap with a first comparable global Water Quality Index (WATQI) as part of the work on the 2008 Environmental Performance Index (Esty et al., 2008), a joint project of the Yale Center for Environmental Law & Policy and Columbia University's Center for International Earth Science Information Network (CIESIN). The EPI's scope is to provide a global assessment of country level environmental performance in the form of a proximity-to-target index in two broad dimensions, environmental health and ecological vitality. Embedded in these two objectives are 25 indicators, each of which is further allocated to a more specific policy category, that cover all environmental media and ranging from air pollutant concentrations to biodiversity and greenhouse gas emissions (Esty et al., 2008).

In addition, the significance of water quality for a broad range of different anthropogenic uses means that it falls within the scope and purview of environmental management activities nationally and beyond. It is thus of interest to assess and compare how well countries are doing in protecting and improving water quality for human and ecological uses. Within the EPI, the global WATQI is part of the ecological water management policy category and thus focuses primarily on the ecosystem impacts of water quality. The motivation for the EPI team and its advisors from UNEP GEMS/Water to develop the WATQI was the lack of a globally comparable index and the paucity in relevant, timely, and comparable data.

2.3. Data

The UNEP GEMS/Water Programme is in a unique position to monitor the state of inland water quality as it maintains the only global database of water quality for inland waters, GEMStat, with over two million entries for lakes, reservoirs, rivers and groundwater systems. Its approximately 3200 monitoring stations located in slightly more than 100 countries include baseline (reference or non-impacted), trend (impacted) and flux (estuarine or brackish water) stations (UNEP GEMS/Water, 2007).

Although the GEMS/Water database is the most comprehensive global database of water quality, there are still substantial gaps in country, temporal, and parameter coverage. For this reason, additional annual average water quality conditions for river and lake monitoring stations reported regularly by European countries to the European Environmental Agency (EEA) were used to augment the GEMS/Water data in the calculation of the index. These data are available in the EEA's online databases on lakes and rivers combined under the name Waterbase. In a few cases, country information has also been supplemented with information from credible national focal points. For example, Niger and Israel provided updated water quality data from their monitoring stations. These sources of data were included in the computation of a Water Quality Index. Taiwan provided data aggregated to index level from its national water monitoring program at a later stage in the EPI production and, while its index value is reported, it was not included in the index calculation.

Data compiled by GEMS/Water and the EEA originate primarily from national agencies and departments responsible for monitoring surface water quality. GEMS/Water is committed to maintaining a database of consistent and reliable quality and has implemented a rigorous quality assurance and control system. Despite attention paid by GEMS/Water and other agencies to ensure the quality of data maintained within water quality monitoring databases, there are a number of issues that GEMS/Water and most other water quality monitoring programs face in the collection of water quality data. A major concern in any water quality monitoring programme is ensuring good geographic representation of monitoring stations and temporal coverage of the same water quality parameters within the area of interest.

At the global scale, approximately 100 countries have provided GEMS/Water with water quality data since the late 1970s. However, the reporting of data is inconsistent, with some countries only supplying a year or two of data and others supplying data on a regular basis. The types of parameters reported are also inconsistent. Some countries only supply basic water quality parameters such as dissolved oxygen, pH, or electrical conductivity, whereas others submit specific parameters (concentrations of metals, pesticides or bacteria). In addition, some countries only supply data from one or a few monitoring stations, or, from mainly impacted sites with very little data from non-impacted or baseline sites, whereas other countries provide water quality data for almost all of their national monitoring stations, representing a gradient from relatively pristine to heavily impacted sites. While legacy issues remain, considerable efforts have been made by GEMS/Water in recent years to improve reporting consistency among countries and to increase global coverage.

The EEA databases contain information on the status and quality of Europe's rivers, lakes, groundwater bodies and transitional, coastal and marine waters, and on the quantity of Europe's water resources. A harmonized and agreed-upon data collection protocol facilitates the compilation of timely, reliable and policy-relevant data from EEA member countries through the former Eionet and now WISE (water information system for Europe) water processes. In this context, WISE ensures that monitoring data are from statistically stratified monitoring sites, are validated, and supported by information on the physical characteristics of the monitored water bodies and on potential pressures influencing water quality. The Waterbase data are thus comparable at the European level (EEA, 2009).

The merging of available data from GEMS/Water, the EEA, and country sources led to a final dataset for 6214 stations in 92 countries. These records represent aggregates over consecutive five year periods.

2.4. Calculation of the Water Quality Index

Available water quality indices and their methodology reflect their specific uses and geographical areas of application (Cude, 2002a; Dinius, 1987; Haire et al., 1991; Hallock, 2002; Harkins, 1974; Horton, 1965; Inhaber, 1974; Nagels et al., 2001; Ott, 1978; Stoner, 1978; Walski and Parker, 1974; Zoeteman, 1973) and most approaches include the following steps:

1. Selection the water quality parameters to be included.
2. Transformation of the raw parameter data onto a common scale.
3. Decision on the relative weights to be allocated to the index components.
4. Specification of the aggregation function, including, where possible, controlling for the sampling design of the water quality monitoring data.

Intended use and other aspects such as the location and specific characteristics of the waterbodies, monitoring sites, and the sampling protocol influence the decision-making in all four steps and the selection of appropriate weighting and aggregation functions remains a challenging issue (Cude, 2002a,b; Nagels et al., 2001; Smith et al., 2002). The WATQI is no exception in this regard and

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the development process is furthermore hampered by considerable amounts of missing data across countries and time. In addition, the goal to integrate the WATQI into the EPI prescribed the use of a proximity-to-target approach and hence the specification of performance targets for all selected water quality parameters.

Following extensive consultation with UNEP GEMS/Water and other experts and taking into account data availability in GEMStat and Waterbase, five water quality parameters were selected:

- dissolved oxygen (DO)
- electrical conductivity (EC)
- pH
- total phosphorus (P)
- total nitrogen (N)

These parameters have demonstrated utility as indicators of the main ecological water quality impairment issues – oxygen depletion, nutrient pollution, acidification, and salinization. The selected parameters are widely used in the literature on measuring water quality (Cude, 2002a; Dinius, 1987; Landwehr, 1976a; Nagels et al., 2001; Parparov et al., 2006; Said et al., 2004). Table 1 describes the relevance of these parameters for ecological vitality.

In addition, the selected parameters are the most consistently reported parameters in the GEMStat and Waterbase databases and therefore provide the most comprehensive picture of water quality globally. However, to further increase global country coverage for the WATQI, substitutes were specified for total phosphorus and total nitrogen in case a country did not have any observations for them. For total phosphorus the selected substitute is orthophosphate and for total nitrogen, the substitutes are, in this order of preference, dissolved inorganic nitrogen, nitrate and nitrite, and ammonia.

After the water quality parameters have been selected, transformation equations to convert the raw data to a common scale, usually an easily readable and communicable scale such as from zero to 100 with pre-determined benchmarks (or water quality classes) such as "excellent", "good", "satisfactory", etc. Similar to the parameter selection process, these transformation equations are often the outcome of expert surveys using questionnaires or other methods (Cude, 2002a; Nagels et al., 2001). The use of transformation equations was not feasible for the WATQI due to the global geographical extent of the index and the anticipated diversity in expert opinions on the shape and location of the transformation function. Instead, GEMS/Water experts were asked to specify performance targets for the water quality parameters that reflect scientific knowledge on their ecological impacts. The raw data were then converted to scale-free proximity-to-target values.

2.4.1. Target specification and transformation to common scale

In the design of the WATQI, UNEP GEMS/Water focused on existing baseline, threshold, guideline or standard values for different water quality parameters that have been set or proposed at the national and regional levels for the protection of ecosystem health (UNEP GEMS/Water, 2006). These guidelines have been established by nations or regional bodies that operate extensive monitoring programs such as Australia and New Zealand (The Australian and New Zealand Environment and Conservation Council), the European Union (The Water Framework Directive), the United Kingdom (Environment Agency), the USA (Environmental Protection Agency) and Canada (Environment Canada). In the case of the nutrients nitrogen and phosphorus, natural variability in background concentrations and the fact that nutrients are rarely present in concentrations that are toxic to aquatic organisms makes it

Table 1
Summary of WATQI parameters, their rationale for inclusion, and their limitations in characterizing water quality at the global level.

Parameter	Code	Unit	Link to ecological vitality	Limitations
Dissolved oxygen	DO	mg of O_2 per liter	Measures oxygen saturation of the waterbody and its ability to sustain aerobic aquatic life and suitability as drinking water; low DO increases conversion of nitrate to nitrite and sulphate to sulphide	Influenced by water temperature (cold water can hold more oxygen); Optimal DO depends on species and intended water use; supersaturation also threatens aquatic life
Electrical conductivity	EC	Micro Siemens per cm	Measures the amount of total dissolved ions in the water and is a proxy for anthropogenic pollution, suitability as drinking water; is also linked to species composition and diversity	Influenced by geology, climate, evaporation, size of water basin relative to size of waterbody, bacterial metabolism in waterbody
pH	pH	No dimension	Measures acidity or alkalinity of waterbody and affects respiration and development of aquatic life as well as bioavailability of soluble metals	Influenced by geology
Total phosphorus	P	mg per liter	Nutrient and limiting factor for algae growth and hence an indicator of eutrophication risk; linked to shifts in species composition	Influenced by geology
• *Orthophosphate*	OP	mg per liter	Most stable form of phosphate, used by plants, that is produced by natural processes but also found in sewage	Cycles rapidly through aquatic environments and can range from <1 to nearly 100% of total phosphorus concentration
Total nitrogen	N	mg per liter	Composed of dissolved and particulate inorganic and organic nitrogen and indicator of eutrophication risk; linked to shifts in species composition	Naturally occurring element influenced by bacteria, phytoplankton, and decomposition of aquatic matter
• *Dissolved inorganic nitrogen*	DN	mg per liter	Component of total nitrogen	Cycles rapidly through aquatic environments and can range from <1 to nearly 100% of total nitrogen concentration
• *Total nitrate and nitrite*	NN	mg per liter	Nitrate is most highly oxidized (nitrification) and most abundant form of nitrogen, toxic to aquatic life in high concentrations; Nitrite is bacterially reduced form of nitrate (denitrification) and major pollutant	Cycles rapidly through aquatic environments and relationship to total nitrogen are not consistent.
• *Ammonia*	AM	mg per liter	In water dissociates into NH^{4+} and OH^- (ammonium hydroxide), which at high pH levels becomes toxic to aquatic life	Cycles rapidly through aquatic environments and relationship to total nitrogen are not consistent.

Note: Substitute parameters are shown in italics.

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Table 2
Performance targets for the selected EPI WATQI parameters.

Parameter	Mesotrophic	Eutrophic	Hypereutrophic	Type of water body	Source
Total phosphorus (mg per liter)	0.010–0.035[a]	0.035–0.100[a]	>0.100[a]	Lakes	OECD (1982)
	0.027[b]	0.084[b]		Lakes and Reservoirs	Wetzel (1983)
	0.010–0.030[a]	0.030–0.100[a]	>0.100[a]	Lakes	Nürnberg (1996)
	0.010–0.020[a]	0.020–0.050[a]	0.050 to >0.100[a,d]	New Zealand lakes	Waikato Regional Council, NZ (1999–2007)
	<0.200[c]	≥0.200[c]		Rivers globally	UNEP GEMS/Water (2006)
	<0.075[c]	≥0.075[c]		Temperate streams in North American and New Zealand	Dodds et al. (1998)
Total nitrogen (mg per liter)	0.350–0.650[a]	0.650–1.20[a]	>1.20[a]	Lakes	Nürnberg (1996)
	0.753[b]	1.875[b]		Lakes and Reservoirs	Wetzel (2001)
	<1.50[c]	≥1.50[c]		Temperate streams in North American and New Zealand	Dodds et al. (1998)

'Mesotrophic', 'Eutrophic' and 'Hypereutrophic' refer to systems with intermediate, high and very high levels of productivity.

[a] Data represent the range of expected concentrations.
[b] Data represent the mean expected concentration.
[c] Data represent the boundary concentration.
[d] Includes a classification for 'supertrophic' as intermediate between eutrophic and hypereutrophic.

Table 3
Performance targets for the selected EPI WQI parameters.

Parameter	Unit	Target	Details	Selected sources
Dissolved oxygen[1]	mg L^{-1}	≥9.5	DO must not be less than target when average water temperatures are ≤20 °C	(1)–(3)
		≥6	DO must not be less than target when average water temperatures are >20 °C	(1)–(3)
pH		6.5–9.0	pH must fall within target range	(1)–(5)
Electrical conductivity	500 µS cm^{-1}	≤500	Conductivity must not exceed target	(1), (2), and (6)–(10)
Total nitrogen	mg L^{-1}	≤1	Total nitrogen must not exceed target	Refer to Table 2
Dissolved inorganic nitrogen	mg L^{-1}	≤0.5	Dissolved inorganic nitrogen must not exceed target	
Nitrate + nitrite	mg L^{-1}	≤0.5	Nitrate + nitrite must not exceed target	
Ammonia	mg L^{-1}	≤0.05	Ammonia must not exceed target	
Total phosphorus	mg L^{-1}	≤0.05	Total phosphorus must not exceed target	Refer to Table 2
Orthophosphate	mg L^{-1}	≤0.025	Orthophosphate must not exceed target	

Note: Substitute parameters are shown in italics.

Sources for targets: (1) ANZECC (Australian and New Zealand Environment and Conservation Council), 1992. Australian Water Quality Guidelines for Fresh and Marine Waters. Canberra, 202 pp. (2) Brazil, 1986. Brazilian Surface Water Quality Guidelines. Resolução Conam No 20., de 18 de junho de 1986. http://www.mma.gov.br/port/conama/res/res86/res2086.html (accessed 31.03.08). (3) CCME (Canadian Council of Ministers of the Environment), 1999. Canadian Environmental Quality Guidelines, Winnipeg. (4) US EPA (United States Environmental Protection Agency), 2006. National Recommended Water Quality Criteria. Office of Water, Office of Science and Technology (4304 T). http://epa.gov/waterscience/criteria/nrwqc-2006.pdf. (5) EEA (European Environment Agency), 2006. Directive 2006/44/EC of 6 September 2006 on the quality of fresh waters needing protection or improvement in order to support fish life. Official Journal of the European Union, L 264/31. (6) Chapman, D. (Ed.), 1996. Water Quality Assessments. A Guide to the Use of Biota, Sediments and Water in Environmental Monitoring, 2nd ed. Published on behalf of UNESCO, WHO, and UNEP. Chapman and Hall, London. (7) Weber-Scannell, P.K., Duffy, L.K., 2007. Effects of total dissolved solids on aquatic organisms: a review of literature and recommendation for salmonid species. Am. J. Environ. Sci., 3, 1–6. (8) Sorensen, D.L., McCarthy, M., Middlebrooks, E.J., Porcella, D.B., 1977. Suspended and dissolved solids effects on freshwater biota: a review. US Environmental Protection Agency, EPA-600/3-77-042. (9) Peterka, J.J., 1972. Effects of saline waters upon survival of fish eggs and larvae and upon the ecology of the fathead minnow in North Dakota. PB-223 017, National Technical Information Service, Springfield, VA 22161. (10) Derry, A.M., Prepas, E.E., Hebert, P.D.N., 2003. A comparison of zooplankton communities in saline lakewater with variable anion composition. Hydrobiologia, 505, 199–215.

difficult to set global water quality targets. Thus, nitrogen and phosphorus targets for the derivation of a global Water Quality Index were chosen to reflect the average boundary concentration between mesotrophic and eutrophic/hypereutrophic systems as reviewed in Table 2.

Guidelines and standards used to set the target values are those that consider water quality primarily from an ecosystem health perspective recognizing their lack of holistic, ecological assessment criteria. Nevertheless, it is understood that existing ecological water quality targets differ according to the ecological uses of water resources, natural background conditions of the water systems, and what is considered 'ideal' for different parts of the world. The targets that resulted from this assessment and decision process are shown in Table 3.

Before converting the station-level monitoring data to proximity-to-target (PTT) values, the distribution of each parameter was examined and, with the exception of pH and DO, found to be highly right skewed. The long, right tails of the parameters would thus affect the distribution of the PTT values by clustering the majority of observations close to the target. To improve the evenness of the spread in the PTT values exceeding the 95th percentile of the data distribution where set to that percentile value, with the exception of pH and DO.[3]

PTT values for each parameter and station were then calculated such that a PTT of 100 corresponds to meeting the target, or falling within the target range in the case of pH, and PTT values closer to zero indicate an increasing distance from the target (target range in the case of PH). The exact equations are shown in Appendix A.

An adjustment to the maximum possible PTT score was made when the preferred indicators of nutrient pollution, i.e., total nitrogen and total phosphorus, were missing and only substitute parameters were available. Thus, the best possible PTT score

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[3] From a statistical perspective, this manipulation affects the distribution of the data by creating local maxima. However, as long as the number of observations exceeding the specified percentile is not overly large, this effect can be ignored (Dixon and Tukey, 1968).

Table 4
Adjustment multipliers for the country-level WATQI on the basis of monitoring station density.

Station density	Multiplier
≥1 station/1000 km^2	1.00
0.1–0.99 stations/1000 km^2	0.95
0.01–0.099 stations/1000 km^2	0.90
0.001–0.0099 stations/1000 km^2	0.85
<0.001 stations/1000 km^2	0.80

for substitute parameters orthophosphate and dissolved inorganic nitrogen is 80, respectively, and for total nitrate and nitrite and ammonia it was set to 60 (cf. Eqs. (5) and (7)–(9) in Appendix A). This decision reflects the superiority of the primary parameters P and N as indicators of water quality and also intended as a signal to countries to monitor and report these important parameters.

2.4.2. *Weighting and aggregation of the index components*

The station-level PTT values were then summed over the available water quality parameters and divided by five to generate a station level WATQI that ranged from 0 to 100. Division by the total number of parameters rather than the number of available parameters ensured that stations with incomplete reporting did not benefit from failing to report one or more of the selected quality parameters.

Next, the station-level WATQIs were averaged to obtain a raw country WATQI using only those stations that report the maximum number of parameters within the country. This approach emphasizes completeness in the parameter count at the expense of station coverage. Since the maximum number of available parameters varies across countries, the range of country WATQIs is based on parameter counts between three (the *min max* parameter count) and five (the *max max* parameter count).

In the final step, the country-level WATQIs were adjusted for the density of monitoring stations based on national water quality monitoring data collected by GEMS/Water to take into account the density of the monitoring network. Ideally, a spatial adjustment would not only correct for variations in station density but also for bias in the location of monitoring stations on the one hand and pressure and exposure points, such as large industrial emitters and population centers, on the other. GEMStat and Waterbase both contain geographical location parameters (latitude and longitude coordinates) for each monitoring station, however, development of an appropriate adjustment methodology was not feasible in the EPI process and could be considered in the future. The adjustment step applied instead used a set of multipliers, derived in consultation with UNEP GEMS/Water experts and shown in Table 4, that is based on the density of the monitoring station network per populated land area, i.e., the land area with a population density of at least 5 persons per km^2 derived from the SEDAC PLACE II dataset (Socioeconomic Data and Applications Center, 2007). The purpose was to adjust the scores of countries that report a very small number of water monitoring stations per populated area relative to those that have a dense network of stations. This is based on the assumption that a denser network, on balance, will offer a much more accurate view of water quality in a country.[4]

The country-level WATQI is available for 92 countries, 87 of which had sufficient data for the remaining 24 EPI indicators to be included in the 2008 EPI. Of the 149 countries in the 2008 EPI, 62 were missing the WATQI. For the majority of these countries the EPI version of the WATQI uses the 33rd percentile of the regional distribution of the WATQI to replace missing values. In a few instances the number of countries with available WATQIs in the region was extremely small and the regional mean WATQI was used with a 10 point penalty.[5] Regions were based on the UNEP regional classification applied in the Global Environmental Outlook (GEO). The complete results are shown in Table A1 in Appendix A. An asterisk indicates the regionally imputed values. This relatively crude estimation procedure does not take into account local variations in hydrology, meteorology, water quality management, regulation, and policies, and many other factors known to influence water quality. Thus, in this paper the more refined hot-deck imputation method is applied.

2.4.3. *Missing data imputation via hot-deck imputation*

Hot-deck imputation derives its name from the "decks" of computer cards (Little and Rubin, 2002). In the context of missing data imputation, these decks represent observations from other cases, called "donor cases" that match the "recipient" case on a set of specified variables from the same data set.

The missing value is imputed by choosing either the closest match or a randomly drawn observed value from the hot deck. If the donor is drawn randomly from the set of matches, the procedure can be repeated multiple times, creating multiply imputed data with the associated benefit of reflecting both sampling and missing data uncertainty.

The advantages of using hot-deck imputation over mean (or percentile) imputation are permissible values from the observed distribution are used as donors and the empirical variances and correlations are better preserved (Little and Rubin, 2002; Schafer and Graham, 2002).

For this study, no station-level information is available for countries with missing WATQI. Therefore, the imputations are generated at the level of the aggregate country WATQIs using additional external information on the geographical, eco-climatic, and socio-economic conditions of the countries (cf. Table 5). Both, natural and socio-economic characteristics are chosen as candidates for the imputation process because both were found useful in explaining and predicting water quality at the country level. For example, even a country located in a disadvantaged eco-climatic zone (e.g., Koeppen eco-climatic zone classification B) can have excellent water quality if pressures on water resources are low or well-managed. Analogously, two countries with rich endowments in freshwater sources may face different water resource management issues due to different levels of socio-economic pressures and variation in resource management capacities.

From an eco-climatic perspective, relevant information is given by the geographical region in which the country is located, the biome and eco-climatic zones that most of its territory belongs to. The eco-climatic zone characterization is based on the Koeppen classification and together with the biome class is drawn from the SEDAC PLACE II data set at Columbia University's Earth Institute (SEDAC, 2007).

The socio-economic variables added to the data can be described as pressure and management indicators with the first group consisting of population density, actual annual renewable water resources per capita, the Water Poverty Index (WPI) developed by the UK-based Centre for Ecology and Hydrology Wallingford (Centre for Ecology and Hydrology, 2002), water stress, and industrial pollution measured in kilograms of BOD per day. The WPI consists of sub-indices measuring resources, access, capacity, use, and environment. Water stress is measured as the percent of the territory where water use exceeds 40% of available freshwater sup-

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[4] This adjustment does not address the spatial location of stations vis-à-vis population centers, agricultural areas, or point sources of pollution, which in future iterations of the WATQI would be useful to consider.

[5] For details, please see Esty et al. (2008) or visit http://epi.yale.edu/Home.

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Table 5
External information added to GEMS and EEA water quality data.

Variable	Source	Rationale
Region	United Nations Environment Programme GEO region classification	Countries in the same region are more likely to face similar water quality challenges
Average GDP per capita 2000–2006 (PPPs, constant 2000 intl. $)	World Bank, 2007 World Development Indicators	Proxy for economic development status
Average population density 2000–2006 (persons/km^2)	World Bank, 2007 World Development Indicators	Proxy for the pressure exerted on water resources
Average actual renewable water resources per capita 2006–2007 (m^3/person/year)	World Resources Institute, Earthtrends database, online	Higher quantities of available freshwater may reduce pressure on water quality
Biome class 2000	Center for International Earth Science Information Network, Columbia University, SEDAC, PLACE II data set	Proxy for ecological conditions that may be related to water quality
Koeppen eco-climatic zone 2000	Center for International Earth Science Information Network, Columbia University, SEDAC, PLACE II data set	Description of climatic factors that can affect water quality
Water Poverty Index 2002 (0–100 with 100 indicating good water provision)	World Resources Institute, Earthtrends database, online	Proxy for the pressure on water resources, which may be related to water quality
Percent of country under water stress	Yale Center for Environmental Law and Policy and Columbia University Center for Earth Science Information Network, 2008 Environmental Protection Index	Stress measure with respect to quantity may also be linked to water quality problems
Percent of population with access to improved sanitation 2004	World Resources Institute, Earthtrends database, online	Proxy for economic development status and associated ability to monitor and manage water quality
Percent of population with access to improved water source 2004	World Resources Institute, Earthtrends database, online	Proxy for economic development status and associated ability to monitor and manage water quality
Average industrial water pollution 1990–2002 (BOD emissions in kg/day)	World Resources Institute, Earthtrends database, online	Proxy for pressure on water quality from industrial activities

ply, a common measure of oversubscription used, for example, by the World Meteorological Organization (Esty et al., 2008, p. 75). The management indicators are the MDG indicators access to improved sanitation and improved drinking water source.

The selected imputation variables were not available for all countries and therefore introduced additional missing values to the data set. To reduce their effect on the imputation procedure, countries missing at least five of the imputation variables were deleted from the data set. For the remaining countries summary statistics for the imputation variables and their correlation with the WATQI are shown in Table 6. Heavily skewed distributions were transformed using the natural logarithm to better approximate normality. Continuous variables were temporarily categorized into quartiles so that an equal number of cases are available in each class rather than opting for an equidistant length of the class intervals. Compared to using quintiles or even smaller intervals, the use of quartiles increased the number of imputed WATQIs due to the increased likelihood of non-zero cell counts in the hot-deck set. However, neither using quintiles nor quartiles yielded a significant increase in imputed WATQIs when all imputation variables were used simultaneously. Thus a subset is chosen containing the variables having the strongest rank correlation with the WATQI. These are the Water Poverty Index ($r = 0.46$), the natural logarithm of actual renewable water resources per capita ($r = 0.37$), the natural logarithm of industrial pollution ($r = 0.32$), access to sanitation ($r = 0.26$), and the natural logarithm of GDP per capita ($r = 0.25$). Access to improved water source also correlates reasonably well with WATQI ($r = 0.24$) but is not included because it also correlates strongly with sanitation and GDP per capita. Biome class is retained due to its relevance as an ecological proxy for water quality.

Using the reduced set of imputation variables the hot-deck imputation procedure then matched covariate values of countries missing WATQI values with those of donor cases and randomly drew an observation from the donor set to impute the missing value with the selected donor's WATQI value.

3. Results

The hot-deck imputation yields an addition of 39 imputed country indices in addition to the 93 (including Taiwan) not imputed WATQI values and they are shown in Table 7.

Table 6
Summary statistics and correlations of imputation variables with the WATQI.

Variable	Transformation	Summary statistics[a]			Correlation with WATQI
		Missing values	Mean	Standard Deviation	
Region class	None	0	–	–	–
Biome class	None	0	–	–	–
Eco-climatic zone	None	0	–	–	–
GDP per capita	Natural logarithm	0	8.50	1.19	0.25
Population density	Natural logarithm	0	4.03	1.41	−0.01
Actual annual renewable water resources	Natural logarithm[b]	0	8.46	1.90	0.37
Water Poverty Index	None	21	56.73	10.16	0.46
Water stress	None	9	13.84	18.51	−0.19
Access to improved sanitation	None	0	69.53	28.07	0.26
Access to improved water source	None	0	82.71	18.48	0.24
Industrial pollution (BOD)	Natural logarithm	44	10.43	1.99	0.32

[a] Summary statistics are shown for the transformed variables where applicable.
[b] A small constant of 0.1 was added to all observations to avoid taking the undefined logarithm of zero. The total data set contains 168 countries and territories.

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Table 7
Comparison of imputed WATQI values using hot-deck imputation and regional 33rd percentiles and mean values with 10-point penalty applied in the 2008 EPI.

Country	Hot-deck imputed WATQI	2008 EPI WATQI	Country	Hot-deck imputed WATQI	2008 EPI WATQI
Antigua & Barbuda	34.81	75.62	Liberia	94.65	52.00
Burundi	76.48	55.27	Madagascar	76.9	57.54
Benin	58.98	52.00	Myanmar	81.78	81.48
Burkina Faso	76.48	52.00	Mozambique	37.44	57.54
Bahrain	82.38	39.89	Nigeria	73.85	52.00
Belarus	93.62	58.92	Nicaragua	71.94	74.21
Belize	92.61	74.21	Nepal	76.9	72.27
Barbados	82.38	75.62	Qatar	82.38	39.89
Central Afr. Rep.	71.11	53.01	Rwanda	76.48	55.27
Cameroon	66.04	53.01	Solomon Islands	94.65	48.73
Congo	94.65	53.01	Sierra Leone	94.65	52.00
Costa Rica	85.56	74.21	Somalia	73.85	55.27
Djibouti	34.89	55.27	Sao Tome & Principe	76.9	53.01
Eritrea	76.48	55.27	Suriname	68.54	69.74
Ethiopia	76.48	55.27	Chad	73.85	53.01
Gambia	85.69	52.00	Togo	58.98	52.00
Guinea-Bissau	71.11	52.00	Ukraine	67.27	58.92
Equ. Guinea	62.24	53.01	Venezuela	62.24	69.74
Guyana	71.94	69.74	Zambia	85.69	57.54
Kuwait	82.38	39.89			

Fig. 1 compares the frequency distributions of the not imputed WATQI, the hot-deck imputed WATQI, and the EPI WATQI. The not-imputed WATQI served as the reference index because it does not contain any potential distortions due to the imputation of missing values using either regional means/percentiles or hot-deck imputation.

The hot-deck imputed WATQI closely resembles the frequency distribution of the not-imputed WATQI, although there is a spike in imputed WATQIs around 70. In contrast, the EPI WATQI frequency distribution is very different from the not imputed WATQI and most imputed WQIs are in the 50–60 and 70–80 points range.

The mean hot-deck imputed WATQI is 76.9 and the standard deviation is 15.7, which is very similar to the mean of 78.0 and standard deviation of 15.9 for the not imputed WATQI. Hot-deck imputation is more successful in preserving the distribution of the data than other imputation methods such as mean imputation. If it can be assumed that the not imputed WATQI for the 88 countries is a good approximation to true but unknown national water quality, which cannot be proven at this time, then this result is encouraging because the hot-deck imputed WATQI resembles this distribution better than the 2008 EPI WATQI that uses regional means and percentiles to impute missing values. Another advantage of the hot-deck method is that only permissible values are imputed because they are directly taken from donor cases.

In contrast, the 2008 EPI WATQI, which includes the 88 original WATQIs (including Taiwan) and regional imputations for 61 countries, relies entirely on geographical location for its imputation algorithm. It has a mean of 67.2, which is statistically significantly smaller (p-value <0.01) than that of the non-imputed WATQI (78.0) and a standard deviation of 15.6. In part, this difference in means can be attributed to the use of the 33rd percentiles and regional means with penalties as the basis for the imputation. However, despite conditioning on geographical location, mean and percentile imputation distorts the distributional characteristics of the data.

From a water management perspective it is important to answer the question ‘Which imputation approach, hot-deck or regional percentile imputation, comes closer to the unknown true distribution of the WATQI?’ The differences between the EPI WATQI and the not imputed WATQI have already been pointed out (cf. Fig. 1). Reviewing the location and socio-economic characteristics of the original 238 countries and territories with missing WATQI yields that the majority of countries lacking a WATQI are small islands countries located in the Caribbean, the South Pacific, and the Western Indian Ocean as well as developing economies in Africa, Central and South America, and Asia. The median GDP per capita in these countries is \$3630 with a range of \$580 in Malawi to \$26420 in Macao. Thus, developing and/or small islands countries are more likely to have a missing WATQI value compared to developed economies in Europe and North America.

But is water quality also generally lower in low-income and small islands countries compared to the developed countries in Central and Western Europe, North America, and Oceania? The evidence for this hypothesis is mixed. On average WATQI values are highest in Australia and New Zealand (95.9), the Caribbean (94.5), and North America (92.5) and lowest in the Mashriq (Middle East, 34.9), the South Pacific (62.9), and Northern and Western Africa (64.3 and 64.8, respectively). Using per capita income and the UNDP's Human Development Index for 2006 (most WATQI values include this year) as proxies for level of development and wealth and population density as a measure of densely populated countries, respectively, correlations with the non-imputed WATQI are at best modest. Per capita income and HDI show a statistically significant positive correlation with the WATQI or $r = 0.25$ and $r = 0.328$, respectively, while population density correlates weakly negatively with water quality ($r = -0.13$).

4. Discussion

The WATQI has several important limitations, chief among them is the persistent lack of sufficient and comparable monitoring data on a broad range of parameters used to characterize water quality. We have compiled what we believe is the most extensive global database of freshwater monitoring data for the selected water quality parameters dissolved oxygen, electrical conductivity, pH-value, nitrogen and phosphorus. However, we do not have enough information on the sampling design used to collect the data and it is likely that quality varies not only across countries but monitoring sites and over time. Discussions with individual countries have revealed that many countries with active water quality monitoring programs are not represented in GEMS-Water, and that even those that are often release data for only a subset of stations from their entire network. Issues of station location (upstream or downstream of industrial areas) and geographic representativity are critical, yet could not be fully addressed in this paper. Nevertheless, we have ensured data quality through extensive checks on the plausibility of the raw data and included only samples with known measurement method in our database.

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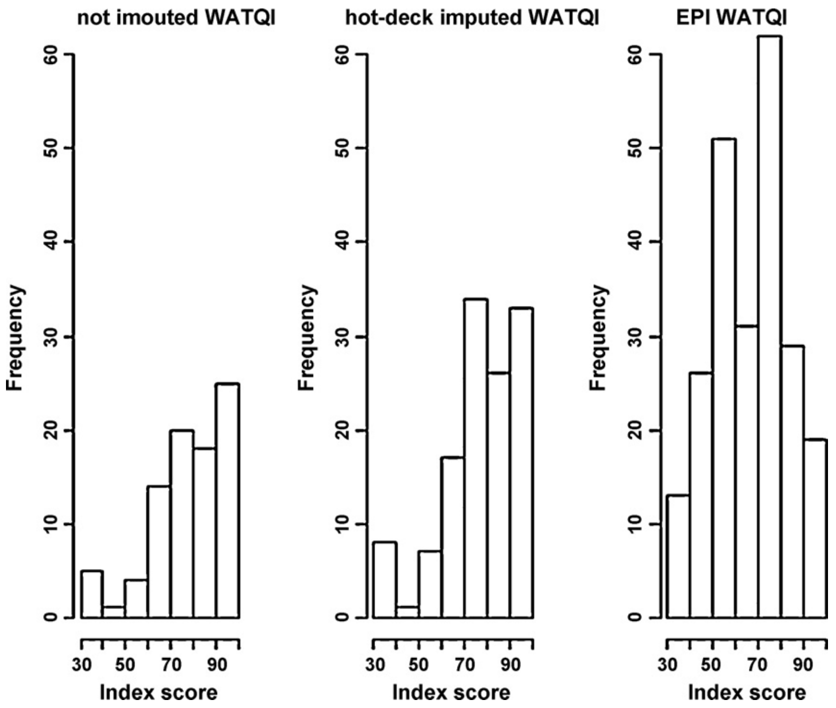

Fig. 1. Comparison of the hot-deck WATQI with the not imputed WATQI, and the 2008 EPI WATQI.

The five parameters (and their substitutes) chosen for inclusion in the index – dissolved oxygen, electrical conductivity, pH value, total nitrogen, and total phosphorus – are widely recognized and used for their relevance in water quality monitoring. The index is the weighted sum of five proximity-to-target sub-indices, one for each parameter.

In addition to their scientific relevance, the selected parameters are also the most frequently reported parameters to the GEMS/Water and the EEA. Nevertheless, data availability was only sufficient to calculate WATQIs for 92 countries, 87 of which are part of the 149 countries included in the 2008 EPI, which used regional percentile values to fill in the remaining 62 country values. The WATQI presented here deviates from the EPI methodology by computing hot-deck imputations for missing data and thereby placing the imputations on a more rigorous statistical basis that also goes beyond geographic proximity as a relevant factor for water quality by considering additional covariates. The procedure essentially replaces missing WATQI values with randomly selected WATQIs from "donor countries" that match the "recipient country" on selected ecological and socio-economic variables that were found to correlate well with the original, not imputed WATQI.

The results expand the original WATQI by 39 countries to 131 countries, thereby increasing geographical coverage by 42%. Further expansion of coverage would require an increase in the interval widths for the water quality parameters to increase the probability that cells used to match donor and recipient cases are not empty. This diminished the strength of the relationships between the WATQI and the selected imputation variables and thereby reduced the quality of the imputations too much. In contrast to the EPI WATQI, the imputed WATQI values do not distort the mean, standard deviation, and frequency distribution of the original, not imputed WATQI.

The validity of the hot-deck imputed WATQI depends, inter alia, on the validity of the assumptions underlying hot-deck imputation. The main assumption, which is also its most restrictive, is that the data are missing completely at random (MCAR), a concept defined by Rubin (1976), which states that the probability that a value is missing does not depend on the missing value or other observed covariates. In a sample survey context, MCAR is often referred to as uniform non-response. In the context of the WATQI it means that the missing data generating mechanism does not depend on the unobserved values or any observed characteristics, i.e., it is independent of the data generating mechanism. This is a very restrictive observation because it implies that other observed characteristics of the countries in the EPI do not correlate with the missingness pattern. Correlation and logistic regression analysis reveals, however, that missingness can be predicted partially by observed variables. For example, missingness in total phosphorus is correlated with missingness in total nitrogen.

Scheffer (2002) has shown, however, that the performance of hot-deck imputation can be acceptable under the less restrictive Missing at Random (MAR) requirement for small to moderate fractions of missing values. The missing data fraction of 42% in the WATQI is moderate to high but we nonetheless think that the advantages of hot-deck imputation compared to mean or percentile imputation outweigh the cost of the likely violated assumption of MCAR.

The potential of the WATQI must be viewed objectively and critically in the context of its ability to inform water policy- and decision-making processes. Just as GDP is only one indicator of an economy's health, the proposed WATQI is only one piece of information that can help understand problems in water quality in a globally comparable manner. The absence of a globally comparable composite water quality measure testifies to the challenges such an undertaking poses but further research and efforts should be expended to fill this critical gap in global environmental monitoring.

The results furthermore demonstrate the complex dimensions of water quality. Water quality is influenced by geographic, climatic, and other physical and ecological criteria – as is reflected in the complex ecological requirements by the European Union's Water Framework Directive (COM, 2000) to achieve "good ecological status" for all freshwater bodies by 2015 – but also by abilities of countries to effectively govern water as a common good, to implement, maintain, and enforce water quality standards and control pressures exerted on it. Level of development as measured by GDP

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per capita and the Human Development Index can hereby function as an enabling factor but itself is not a sufficient condition for healthy water quality. Pressures in the form of population density and industrial pollution can be but are not inevitably linked with poor water quality. Further research is necessary into the balancing dynamics of pressures, governance, and management systems but the WATQI is a first step towards permitting cross-country analyses into the state of freshwater systems and identification of best practices for their effective management.

Necessary steps towards globally comparable, timely, and reliable information on freshwater quality must include strengthening and expanding national data collection systems through increased funding for stations and training of laboratory and field technicians coupled with sustained maintenance of monitoring stations. In addition, efforts by UNEP GEMS/Water and EEA to further harmonize siting of monitoring stations, probe collection and analysis protocols, and compatible data storage and transfer systems for timely and accurate data transmittal should be continued.

Furthermore, the information flow from local monitoring stations to national statistical offices and finally to institutions such as UNEP GEMS/Water and EEA must work in both directions so that ultimately water resource managers at the local level have the necessary information to detect problems early on, to monitor long-term trends robustly and reliably, and to be able to compare performance with similar settings in other parts of the country or abroad. This will ultimately require a much finer spatial resolution along administrative or watershed boundaries to gain an understanding of the pressures of point and non-point sources of pollution on water quality, water use patterns, and the ecological conditions impacted by them.

The proposed WATQI is not intended to provide management and decision-making input at the local water management level but to foster global research and multi-stakeholder dialogue on the issue of water quality and, most importantly, the need to expand the currently very limited data basis for tracking water quality globally at the national level and below. As United Nations experts recently pointed out, improving water quality and sanitation is one of the most profitable and beneficial investments a country can make, generating estimated returns of at least $9 for every dollar directed towards improvements (Doyle, 2008). Thus, every step towards global water quality monitoring can be expected to lead to better planning and decision-making and in turn reduce poverty and improve both human and ecological health. The proposed WATQI can help identify problems and track success in the sustainable management of water resources.

5. Conclusions

This paper presents a first global, country-level Water Quality Index (WATQI) as an input to ongoing research and policy debates on the measurement and management of freshwater quality. To this end, a composite index was developed based on data from the UNEP GEMS/Water programme and the European Environment Agency (EEA).

It is concluded that hot-deck imputation can improve geographical coverage of the WATQI introduced in the 2008 EPI. Its main policy relevance lies in applying a coherent, scientifically informed methodology for computing a comparable country-level water quality indicator that can be used to track water quality over time and space. The WATQI methodology as a composite indicator of proximity-to-target sub-indices not only facilitates its interpretation with values of 100 equating to meeting all of the established water quality criteria while increasing distance from 100 indicates deterioration of water quality on at least one criterion but also allows the immediate identification of the problem areas, e.g., excessive eutrophication signaled by low proximity-to-target values for total phosphorus and nitrogen.

Acknowledgments

The authors wish to thank the team of the 2008 EPI for their valuable comments on an earlier draft of this paper. The WATQI also benefited from the input of the EPI lead scientific experts and other contributors as well as two anonymous referees. The work was in part supported by grants from the Coca Cola Foundation, The Samuel Family Foundation, and the Betsy and Jesse Fink Foundation to the Yale Center for Environmental Law and Policy.

Appendix A.

In Eqs. (1)–(9), *w* indicates the winsorized raw station value and PTT the proximity-to-target station value. Subscripts *i* and *j* denote the country and station, respectively, and *max* or *min* the observed (winsorized) maximum or minimum for country *i* and station *j*. Acronyms for the parameters are those shown in Table 1, i.e., DO for dissolved oxygen, EC for electrical conductivity, PH for pH, P for total phosphorus, OP for orthophosphate, N for total nitrogen, DN for dissolved inorganic nitrogen, NN for nitrate and nitrite, and AM for ammonia. The target value of a parameter is denoted by *t*.

$$\mathrm{DO}_{i,j}^{\mathrm{PTT}}=\begin{cases}100,\ \mathrm{DO}_{i,j}\geq t^{\mathrm{DO}}\\[4pt] 100-100\times\dfrac{|t^{\mathrm{DO}}-\mathrm{DO}_{i,j}|}{t^{\mathrm{DO}}-\mathrm{DO}_{\mathrm{min}}},\ \mathrm{DO}_{i,j}<t^{\mathrm{DO}}\end{cases}\tag{1}$$

$$\mathrm{EC}_{i,j}^{\mathrm{PTT}}=\begin{cases}100,\ \mathrm{EC}_{i,j}^{w}\leq t^{\mathrm{EC}}\\[4pt] 100-100\times\dfrac{|t^{\mathrm{EC}}-\mathrm{EC}_{i,j}^{w}|}{\mathrm{EC}_{\mathrm{max}}^{w}-t^{\mathrm{EC}}},\ \mathrm{EC}_{i,j}^{w}<t^{\mathrm{EC}}\end{cases}\tag{2}$$

$$\mathrm{PH}_{i,j}^{\mathrm{PTT}}=\begin{cases}100,\ t_1^{\mathrm{PH}}\leq \mathrm{PH}_{i,j}\leq t_2^{\mathrm{PH}}\\[4pt] 100-100\times\dfrac{t_1^{\mathrm{PH}}-\mathrm{PH}_{i,j}}{t_1^{\mathrm{PH}}-\mathrm{PH}_{\mathrm{min}}},\ \mathrm{PH}_{i,j}<t_1^{\mathrm{PH}}\\[4pt] 100-100\times\dfrac{\mathrm{PH}_{i,j}-t_2^{\mathrm{PH}}}{\mathrm{PH}_{\mathrm{max}}-t_2^{\mathrm{PH}}},\ \mathrm{PH}_{i,j}>t_2^{\mathrm{PH}}\end{cases}\tag{3}$$

$$\mathrm{P}_{i,j}^{\mathrm{PTT}}=\begin{cases}100,\ \mathrm{P}_{i,j}^{w}\leq t^{\mathrm{P}}\\[4pt] 100-100\times\dfrac{|t^{\mathrm{P}}-\mathrm{P}_{i,j}^{w}|}{\mathrm{P}_{i,j}^{w}-t^{\mathrm{P}}},\ \mathrm{P}_{i,j}^{w}<t^{\mathrm{P}}\end{cases}\tag{4}$$

$$\mathrm{OP}_{i,j}^{\mathrm{PTT}}=\begin{cases}80,\ \mathrm{OP}_{i,j}^{w}\leq t^{\mathrm{OP}}\\[4pt] 80-80\times\dfrac{|t^{\mathrm{OP}}-\mathrm{OP}_{i,j}^{w}|}{\mathrm{OP}_{\mathrm{max}}-t^{\mathrm{OP}}},\ \mathrm{OP}_{i,j}^{w}<t^{\mathrm{OP}}\end{cases}\tag{5}$$

$$\mathrm{N}_{i,j}^{\mathrm{PTT}}=\begin{cases}100,\ \mathrm{N}_{i,j}^{w}\leq t^{\mathrm{N}}\\[4pt] 100-100\times\dfrac{|t^{\mathrm{N}}-\mathrm{N}_{i,j}^{w}|}{\mathrm{N}_{\mathrm{max}}^{w}-t^{\mathrm{N}}},\ \mathrm{N}_{i,j}^{w}<t^{\mathrm{N}}\end{cases}\tag{6}$$

$$\mathrm{DN}_{i,j}^{\mathrm{PTT}}=\begin{cases}80,\ \mathrm{DN}_{i,j}^{w}\leq t^{\mathrm{DN}}\\[4pt] 80-80\times\dfrac{|t^{\mathrm{DN}}-\mathrm{DN}_{i,j}^{w}|}{\mathrm{DN}_{\mathrm{max}}^{w}-t^{\mathrm{DN}}},\ \mathrm{DN}_{i,j}^{w}<t^{\mathrm{DN}}\end{cases}\tag{7}$$

$$\mathrm{NN}_{i,j}^{\mathrm{PTT}}=\begin{cases}60,\ \mathrm{NN}_{i,j}^{w}\leq t^{\mathrm{NN}}\\[4pt] 60-60\times\dfrac{|t^{\mathrm{NN}}-\mathrm{NN}_{i,j}^{w}|}{\mathrm{NN}_{\mathrm{max}}^{w}-t^{\mathrm{NN}}},\ \mathrm{NN}_{i,j}^{w}<t^{\mathrm{NN}}\end{cases}\tag{8}$$

$$\mathrm{AM}_{i,j}^{\mathrm{PTT}}=\begin{cases}60,\ \mathrm{AM}_{i,j}^{w}\leq t^{\mathrm{AM}}\\[4pt] 60-60\times\dfrac{|t^{\mathrm{AM}}-\mathrm{AM}_{i,j}^{w}|}{\mathrm{AM}_{\mathrm{max}}^{w}-t^{\mathrm{AM}}},\ \mathrm{AM}_{i,j}^{w}<t^{\mathrm{AM}}\end{cases}\tag{9}$$

See Table A1.

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Table A1
Results for the Water Quality Index in the 2008 Environmental Performance Index. Countries are listed in alphabetical order and an asterisk indicates imputations using the regional 33rd percentile or mean with a 10 point penalty.

Country	EPI WATQI	Country	EPI WATQI	Country	EPI WATQI	Country	EPI WATQI
Albania	95.79	Dom. Rep.*	75.62	Latvia	97.62	Senegal	69.68
Algeria	37.67	Ecuador	79.33	Lebanon*	39.89	Sierra Leone*	52.00
Angola*	57.54	Egypt	77.98	Lithuania	97.71	Slovakia	70.74
Argentina	85.80	El Salvador*	74.21	Luxembourg	65.30	Slovenia	97.62
Armenia*	58.92	Eritrea*	55.27	Macedonia	63.60	Solomon Isl.*	48.73
Australia	85.17	Estonia	76.40	Madagascar*	57.54	South Africa	66.33
Austria	75.85	Ethiopia*	55.27	Malawi*	57.54	South Korea*	87.34
Azerbaijan*	58.92	Fiji	83.46	Malaysia	81.74	Spain	81.83
Bangladesh	75.52	Finland	99.06	Mali	81.15	Sri Lanka	86.51
Belarus*	58.92	France	77.44	Mauritania*	52.00	Sudan	67.04
Belgium	75.70	Gabon*	53.01	Mauritius*	57.54	Swaziland*	57.54
Belize*	74.21	Georgia*	58.92	Mexico	70.97	Sweden	96.74
Benin*	52.00	Germany	85.59	Moldova*	58.92	Switzerland	93.33
Bolivia	66.18	Ghana	65.51	Mongolia	66.73	Syria*	39.89
Bos. & Herzeg.	90.88	Greece	86.62	Morocco	65.06	Taiwan	65.30
Botswana*	57.54	Guatemala	82.03	Mozambique*	57.54	Tajikistan*	65.60
Brazil	84.31	Guinea*	52.00	Myanmar*	81.48	Tanzania	68.75
Bulgaria	95.45	G.-Bissau*	52.00	Namibia*	57.54	Thailand	87.77
Burkina Faso*	52.00	Guyana*	69.74	Nepal*	72.27	Togo*	52.00
Burundi*	55.27	Haiti*	75.62	Netherlands	78.49	Trin. & Tob.*	75.62
Cambodia	68.40	Honduras*	74.21	New Zealand	99.41	Tunisia	63.76
Cameroon*	53.01	Hungary	91.76	Nicaragua*	74.21	Turkey	72.33
Canada	92.52	Iceland	57.00	Niger	52.75	Turkmenistan*	65.60
Ctrl. Af. Rep.*	53.01	India	80.61	Nigeria*	52.00	Uganda	56.75
Chad*	53.01	Indonesia	83.81	Norway	94.70	Ukraine*	58.92
Chile	74.32	Iran	70.74	Oman*	39.89	UAE*	39.89
China	76.37	Iraq	52.72	Pakistan	64.68	UK	90.48
Colombia	71.74	Ireland	79.29	Panama	85.42	United States	81.77
Congo*	53.01	Israel	80.65	PNG	34.00	Uruguay	88.31
Costa Rica*	74.21	Italy	95.69	Paraguay*	69.74	Uzbekistan*	65.60
Côte d'Ivoire	40.92	Jamaica*	75.62	Peru	60.21	Venezuela*	69.74
Croatia	90.44	Japan	87.20	Philippines	64.29	Viet Nam	87.08
Cuba	85.62	Jordan	47.06	Poland	80.81	Yemen*	39.89
Cyprus	60.55	Kazakhstan*	65.60	Portugal	91.71	Zambia*	57.54
Czech Rep.	41.89	Kenya	73.79	Romania	70.74	Zimbabwe*	57.54
Dem.Rep.Congo*	63.01	Kuwait*	39.89	Russia	68.92		
Denmark	81.52	Kyrgyzstan*	65.60	Rwanda*	55.27		
Djibouti*	55.27	Laos	88.26	Saudi Arabia*	39.89		

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Please cite this article in press as: Srebotnjak, T., et al., A global Water Quality Index and hot-deck imputation of missing data. Ecol. Indicat. (2011), doi:10.1016/j.ecolind.2011.04.023

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