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

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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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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-

[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.