Water Quality: Development of an index to assess country performance

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Introduction

The development of a composite index of water quality will allow assessment of the overall quality of inland surface water resources as it relates to both human and aquatic ecosystem health.

Policy Focus

Water is ranked as second only to oxygen as essential for all life, and access to fresh water and sanitation services is a precondition to all the other internationally agreed goals and targets, including the eight Millennium Development Goals (MDGs) that were established by the United Nations in 2000 and expanded upon in 2002 at the World Summit on Sustainable Development. While water quality management contributes both directly and indirectly to achieving all eight MDGs, it is most closely tied to the targets of Goal 7, to ensure environmental sustainability (UNEP GEMS/Water 2007).

By focusing on water quality, water, sanitation and aquatic biodiversity targets of the MDGs can be met. The way we perceive nature and the value of the goods and services that aquatic resources provide to people is fundamental to peace, security and prosperity. Water is vital to the survival of ecosystems, and in turn ecosystems help to regulate the quantity and quality of water.

From a human health perspective, it is estimated that 1.1 billion people do not have access to safe drinking water. However, if an initial investment is made to improve the quality of water, the economic benefits will increase. For example, people with access to safer, cleaner and healthier water and sanitation facilities would become sick less often, and reduce the burden on health care. They would also be able to lead more productive lives (WHO/UNICEF JMP 2004).

From an environmental perspective, the maintenance of good quality water is essential to the protection of aquatic life and reducing the loss of aquatic biodiversity. The demand to supply water for domestic, agricultural, and/or industrial use to a growing population has led to extensive modifications of inland waters (UNEP GEMS/Water 2006). These modifications have led to habitat loss, pollution, introduction of invasive species and manipulation of flows by the construction of dams and levees, which has ultimately resulted in losses of biodiversity. The loss is so great that the Convention on Biological Diversity (CBD) 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 (CBD, 2001). The monitoring of water quality on a global basis is essential for isolating areas that are declining in water quality and establishing successful techniques in areas of improvement.

What is water quality?

There are many different physical and chemical parameters that can be used to measure water quality and, therefore, there is no one 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 human consumption), 'quality for food' (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.

By regularly monitoring the physical and chemical makeup of water quality, it is possible to detect changes (both good and bad) and implement response measures to mitigate detrimental change before a situation worsens. Monitoring data are essential in identifying hot spots or areas of concern that require immediate attention; in other words, it enables attention to be focused where it is needed the most. At the same time, water quality monitoring data can be used to track response to management regimes aimed at improving water quality.

From a global perspective, it is important to identify a few consistent measurements that provide insight into the general quality of surface waters and that can be monitored easily, by all, on a regular basis. The parameters used here to quantify water quality on a country by country basis were chosen to represent a number of key environmental issues that have global relevance, including organic pollution, nutrient pollution, acidification, and salinisation, and together allow an assessment of overall water quality. The parameters are not meant to be all encompassing; that is, they cannot necessarily identify specific contaminants or assess the suitability of the water for specific uses. However, by using these parameters it is possible to assess and compare the general status of surface water quality in relation to environmental concerns.

The following section outlines the five water quality parameters chosen for inclusion in the water quality index.

Dissolved oxygen (DO)

DO is the measure of free (i.e., not chemically combined) oxygen dissolved in water. It is essential to the metabolism of all aerobic aquatic organisms and at reduced levels has been shown to cause both lethal and sublethal effects. DO levels can fluctuate on a daily, seasonal, and annual basis, and the concentration at which a certain amount is required by all aquatic organisms to survive will differ depending on species and life-stage. The effects of low DO on aquatic organisms have been reviewed extensively (Pollock et al, 2007; Barton and Taylor, 1996; Davis, 1975).

DO is also important when assessing the suitability of water for drinking. Low DO in source water can increase the conversion of nitrate to nitrite and sulphate to sulphide as well as increase the concentration of ferrous iron in solution, leading to discoloration in drinking water (WHO, 2004).

Low DO can occur due to the addition of organic pollutants and nutrients that fuel bacterial and algal production and respiration, leading to the net consumption of oxygen in the water column (Correll, 1998; Barton and Tayler, 1996). Sources of such pollutants include agricultural runoff from manure and fertilizer, municipal areas (municipal wastewater effluent and stormwater drainage), and industrial areas (e.g., pulp and paper mill effluents). As such, the measure of dissolved oxygen will provide a good indication of the state of inland water with respect to nutrient and/or organic pollution.

pH

pH, which is the measure of the acidity or alkalinity of a water body, is an important parameter of water quality in inland waters in that it can affect aquatic organisms both directly through impairing respiration, growth and development of fish, and indirectly, through increasing the bioavailability of certain metals such as aluminium and nickel. The effects of pH have been well documented in both fish (Alabaster and Lloyd, 1982; Fromm, 1980; Schofield, 1976) and invertebrates (Hendrey et al, 1976). pH is also important in assessing the suitability of water for drinking (WHO, 2004).

Acidification in aquatic environments can occur naturally by the breakdown of organic matter resulting in organic acids, by acid precipitation which is related to air emissions of sulfuric and nitric oxides from predominantly industrial sources, or through discharge of acid mine drainage and some industrial effluents (UNEP GEMS/Water 2006). Aquatic organisms have differing tolerances to acidic waters, but species diversity generally decreases as pH of a body of water declines. Young organisms tend to be more sensitive to acidic waters than adults, which can impair reproductive success of some species (UNEP GEMS/Water 2006).

The inclusion of pH into a general index of water quality will provide a good indication of the state of inland water with respect to acidification and to the suitability of water for drinking.

Conductivity

Conductivity is a measure of the ability of water to carry an electric current which is dependent on the presence of ions. It is often used as an indirect measure of salinity and total dissolved solids (TDS). Total dissolved solids can also be estimated from conductivity by multiplying conductivity by an empirical factor (APHA, 1995). Increases in salinity have been shown to reduce biodiversity and alter community composition by excluding sensitive species (Weber-Scannell and Duffy, 2007). An inverse relationship between salinity and aquatic biodiversity has been documented (Derry et al, 2003).

Inorganic compounds are good conductors compared to organic compounds and, as such, increases in conductivity can occur due to the input of industrial effluents, such as metal mining, making conductivity a good indicator of inorganic pollution. Salinity is of particular concern in agricultural areas where low conductivity is used to determine suitability of water for agricultural use (Hart et al, 1991). High salinity and/or TDS levels are also of concern when determining suitability of water for drinking due to objectionable taste (WHO, 2004). Therefore, measuring conductivity will provide a good indication of the state of inland water with respect to the suitability of water for both aquatic life, and for treatment for agriculture and drinking.

Nutrients: Nitrogen and Phosphorus

Nitrogen and phosphorus are naturally-occurring elements essential for all living organisms and are often found in growth-limiting concentrations in aquatic environments. Increases in nitrogen and/or phosphorus in natural waters, largely as a result of human activities in the drainage basin (e.g., from agricultural runoff from manure and synthetic fertilizers and from municipal and industrial wastewater discharge), can result in increased biological productivity of a water body. Although this is not always a negative effect, and nitrogen and phosphorus are rarely if ever present in toxic concentrations, nutrient increases can lead to shifts in aquatic community composition and loss of endemic species, and high algal and aquatic plant productivity can lead to depletion of dissolved oxygen in the water column which can threaten survival of fish and invertebrates.

The process of nutrient enrichment of a body of water is termed ‘eutrophication’ and phosphorus and nitrogen are the primary drivers of the process which has been, and continues to be, a major problem for water quality globally. The inclusion of nutrients into the water quality index will provide a direct assessment of the state of rivers and lakes with regards to eutrophication.

Targets

Water quality monitoring data are most easily interpreted when there is a benchmark or target for a parameter against which individual observations may be compared: in some cases, a target may be a human or ecological threshold beyond which life is impaired; in other cases, a target may be a historical value or a natural background concentration that can serve as a goal for water quality management programmes to reach through intervention and protection of water resources.

Setting realistic targets for water quality is essential to identifying areas of concern as well as to working towards improving water quality on a station by station and country by country basis. Probably the most widely recognized international targets for water quality are the World Health Organization Drinking Water Quality Guidelines (WHO 2004) and although these are an excellent resource for ensuring safe drinking water quality and protecting human health, they do not address issues of environmental degradation of aquatic resources.

By comparison, there are a number of 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 regions that have comprehensive monitoring programmes 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). Guidelines and standards differ according to required uses of a body of water (e.g., for human consumption, recreation, protection of aquatic life, agriculture) and the actual values may vary according to natural background conditions of the systems and what is considered 'ideal' for different parts of the world.

In some cases, even national targets do not exist for the parameters used in the index described here. This typically occurs when a parameter is not toxic at naturally occurring concentrations and/or when natural background concentrations are highly variable and, therefore, a reasonable target in one region might be impractical in another region.

The following sections describe each parameter used in the water quality index and the targets used as a basis against which observations can be compared. Targets chosen are also summarized in Table 1.

Table 1. Summary of targets for water quality parameters included in water quality index.

Parameter	**Target**	**Details**
Dissolved oxygen	6 mg L^{-1}	DO must not be less than target when average water temperatures are > 20 ºC
	9.5 mg L^{-1}	DO must not be less than target when average water temperatures are ≤ 20 ºC
pH	6.5 – 9	pH must fall within target range
Conductivity	500 µS cm^{-1}	Conductivity must not exceed target
Nitrogen		
Total	1 mg L^{-1}	Total nitrogen must not exceed target
Dissolved inorganic	0.5 mg L^{-1}	Dissolved inorganic nitrogen must not exceed target
Nitrate + nitrite	0.5 mg L^{-1}	Nitrate + nitrite must not exceed target
Ammonia	0.05 mg L^{-1}	Ammonia must not exceed target
Phosphorus		
Total	0.05 mg L^{-1}	Total phosphorus must not exceed target
Orthophosphate	0.025 mg L^{-1}	Orthophosphate must not exceed target

Dissolved oxygen target

The lowest acceptable dissolved oxygen concentration for aquatic life, as set by the Canadian Council of Ministers of the Environment (CCME, 1999), ranges from 6 mg L^{-1} in warm water to 9.5 mg L^{-1} in cold water for the protection of early life stages of fish. These targets were derived from the US Environmental Protection Agency's "slight production impairment" estimates (CCME, 1999). The target is in agreement with the Australian guidelines for protection of freshwater ecosystems and the Brazilian guideline for Class 1 waters, that recommend DO be greater than 6 mg L^{-1} (ANZECC, 1992, Brazil 1986).

Since dissolved oxygen is temperature dependent, targets for the global water quality index developed here were chosen such that monitoring stations where average water temperatures are > 20 ºC must have a minimum DO concentration of 6 mg L^{-1}; stations with cooler average water temperatures (i.e., ≤ 20 ºC) must have a minimum DO concentration of 9.5 mg L^{-1}.

pH target

The Canadian Council of Ministers of the Environment (CCME, 1999) set a guideline of pH 6.5 – 9.0 for the protection of aquatic life. That is, pH should not measure below 6.5 or above 9.0. This target is in agreement with the US EPA (US EPA 2006), Australian water quality guidelines (ANZECC, 1992) and the European Union (EEA, 2006). In addition WHO (2004) suggest an optimum pH range of 6.5-9.5 for drinking water; if the pH was out of this range, the suitability of the water for drinking would be markedly impaired. Brazilian water quality guidelines for Class 1 waters recommend that pH be between 6.0 and 9.0 (Brazil 1986).

The target range for pH used in the global index of water quality developed here is pH = 6.5 to 9.0.

Conductivity target

The mean salinity of the worlds rivers is approximately 120 mg l^{-1} TDS (Weber-Scannell and Duffy, 2007) which converts to approximately 220 µS cm^{-1}. However, conductivities in fresh waters can range between 10 and 1,000 µS cm^{-1} and in highly polluted rivers conductivities can exceed 1000 µs cm^{-1} (Chapman, 1996).

A number of studies have identified the effects of TDS on aquatic organisms. These include reduced egg survival and fertilization rates in fish (Peterka, 1972) as well as reduced productivity and growth in algae (LeBlond and Duffy 2001, Sorensen et al, 1977) at concentrations above 275 mg L^{-1} TDS (approximately 500 µs cm^{-1}). Derry et al (2003) found that when TDS increased from 270 to 1170 mg L^{-1} (approximately 500 to 1500 µS cm^{-1}), populations of the aquatic plants *Ceratophyllum demersum* and *Typha* sp. were nearly eliminated.

There are no globally agreed upon guidelines or targets for TDS or conductivity. Australia and New Zealand have set guidelines for salinity that include a conversion to conductivity (ANZECC, 1992). Default trigger values (which refer to slightly to moderately disturbed rivers) for conductivities for upland and lowland rivers nationally in Australia range between 120 and 300 µs cm^{-1}. Brazil (1986) recommends that total dissolved solids not exceed 500 mg L^{-1} (~ 780 µS cm^{-1}) for class 1 fresh waters, used for the protection of aquatic life, irrigation of crops, and recreation.

Based on this information a conductivity target of 500 µS cm^{-1} was chosen.

Nutrients target

Although considerable research has been conducted to identify benchmarks for ‘good’ nutrient concentrations in inland waters, natural variability in background concentrations and the fact that nutrients are rarely present in concentrations that are toxic to aquatic organisms makes it difficult to set global water quality targets (UNEP GEMS/Water 2006; Dodds et al. 1998; Dodds 2002; Wetzel 2003). 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 (reviewed in Table 1, Appendix 1). Dissolved nutrient forms, which tend to cycle very rapidly through aquatic environments, can range from <1 to nearly 100 % of total nutrient concentrations across a broad range of aquatic environments, making it difficult to set boundary concentrations for dissolved forms (Dodds 2003). Target concentrations for dissolved nitrogen and phosphorus were set at one half total nutrient concentrations; ammonia concentrations were set at 1/10 of the dissolved nitrogen target, since ammonia concentrations typically are quite low relative to total nitrogen concentrations.

Potential metrics

Because water quality is a function of a number of different physical and chemical parameters measured during routine water quality monitoring, as outlined above, a global index of the general status of water quality, ranked on a country by country basis, is best developed as a composite index of several key parameters.

How do we interpret monitoring results of complex datasets?

Water quality datasets are necessarily complex and the distillation of multiple measurements of several parameters over time and over space into a single estimate of overall water quality is difficult.

There is considerable debate as to which measures should be included in the derivation of an index, and what type of information such a composite index is able to provide to the general public and to policy makers. However, a number of countries have begun the process of developing composite indices of water quality to describe the state of their domestic waters, including the United States of America (Cude, 2001), Taiwan (Liou et al, 2004), Argentina (Pesce and Wunderlin, 2000), Australia (ISC, 2005), Canada (Khan et al. 2003; Lumb et al. 2006; CCME 2001) and New Zealand (Nagels et al, 2001). Similar to indices of economic strength, such as Gross Domestic Product (GDP), these water quality indices take information from a number of sources and combine them to develop an overall snapshot of the state of the national system. In the case of inland waters, the information used to generate the indices typically consists of concentrations of a number of different water quality parameters measured as part of routine national, regional, and local monitoring programmes.

What data sets exist?

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 is an online global database of water quality maintained by GEMS/Water that has over two million entries for lakes, reservoirs, rivers and groundwater systems, and its over 3000 monitoring stations include baseline (reference or non-impacted), trend (impacted) and flux (at the mouth of large rivers that discharge into the oceans) stations.

While the GEMS/Water database is the most comprehensive global database of water quality, there are still gaps in country coverage. European countries regularly report annual average water quality conditions for river and lake monitoring stations to the European Environment Agency (EEA) and these data are available on the internet. EEA data were also used in the derivation of this index.

Country information has also been supplemented by certain focal points: in the case of the EPI, Niger and Israel provided updated data for the computation of a water quality index.

The compilation of data from several sources led to a final dataset that consisted of 6214 monitoring stations from 92 countries.

How reliable are the data?

The data used in the compilation of the index 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.

The goals of the GEMS/Water Quality Assurance and Control systems are to:

- Ensure the comparability and validity of water quality analyses performed by laboratories around the world;
- Encourage a commitment to data integrity, accessibility, and interoperability; and,
- Facilitate an international information exchange on methods and other technical references.

Data issues

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 programmes 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 are also inconsistent; certain countries only supply basic water quality parameters, whereas others supply specific parameters (metals, pesticides or bacteria) with little or no basic water quality data (i.e. no dissolved oxygen, pH or conductivity). 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. Considerable efforts have been made in recent years to improve reporting consistency among countries and to increase global coverage; however, legacy issues remain in the database, and these reflect inconsistent reporting patterns through time and space.

The parameters chosen to be included in the development of a water quality index for the EPI were selected for two reasons. First, they are good indicators of specific issues relevant on a global basis (eutrophication, nutrient pollution, acidification, salinization). Second, the parameters were chosen because they are the most consistently reported; that is, we have the most data for these parameters compared to other relevant parameters that were not included.

Rationale for recommended metrics

Derivation of the water quality index

The water quality index developed for the EPI relies on station by station measurements of the parameters included in the derivation of the index (i.e., DO, pH, conductivity, total nitrogen, and total phosphorus). Concentrations were averaged annually and subsequent overall average concentrations of each of the measured parameters at each station were calculated for up to the five most recent years for which data were available. Average parameter concentrations at each station were assigned a maximum possible score of 100 if targets were met; if targets were not met then a proximity-to-target (PTT) score was assigned, following winsorization of the entire dataset for that parameter.

Whenever possible, total nutrient concentrations were chosen for inclusion in the index over dissolved nutrient concentrations because they provide a better indication of the true nutrient status of a body of water (Dodds 2003). When only dissolved nutrient forms were available, a penalty was applied so that the maximum possible score for nutrients was 80 (dissolved inorganic nitrogen or orthophosphate) or 60 (nitrate+nitrite or ammonia). Monitoring stations that did not report a particular parameter were assigned a score of zero for that parameter.

The average of parameter PTT scores was used to calculate a composite index value at each station that ranged from a possible 0 to 100, with 100 indicating that all five parameters were reported and met the targets at the station in question. Stations that reported values for only three of the five parameters could only receive a maximum total score of 60 if all three parameters met the targets. In this way, stations that under-reported in terms of water quality parameters could not rank as high as those that reported all five parameters.

Country level index scores were derived by computing the average station score for the best-reported monitoring stations within a country. That is, if the maximum number of parameters reported at any one station in a country was five, then only stations that reported five parameters were included in that country's index score. A total of 92 countries and 2127 surface water monitoring stations were included in the derivation of the index, which represents the most complete picture of surface water globally, to our knowledge.

Country index scores were adjusted according to the density of all monitoring stations (i.e., not just the stations included in index computations), to account for the fact that some countries monitor and report water quality for many stations, whereas other countries report and monitor water quality for only a few stations. Countries with high station densities (≥ 1 station / 1000 km^2 populated land area) received no adjustment to their scores, whereas countries with very low station densities (≤ 1 station / 10,000,000 km^2) had index values that were adjusted down by up to 80% (Appendix 2).

Countries were ranked from highest to lowest index scores to illustrate the gradient from good to poor water quality (Figure 1).

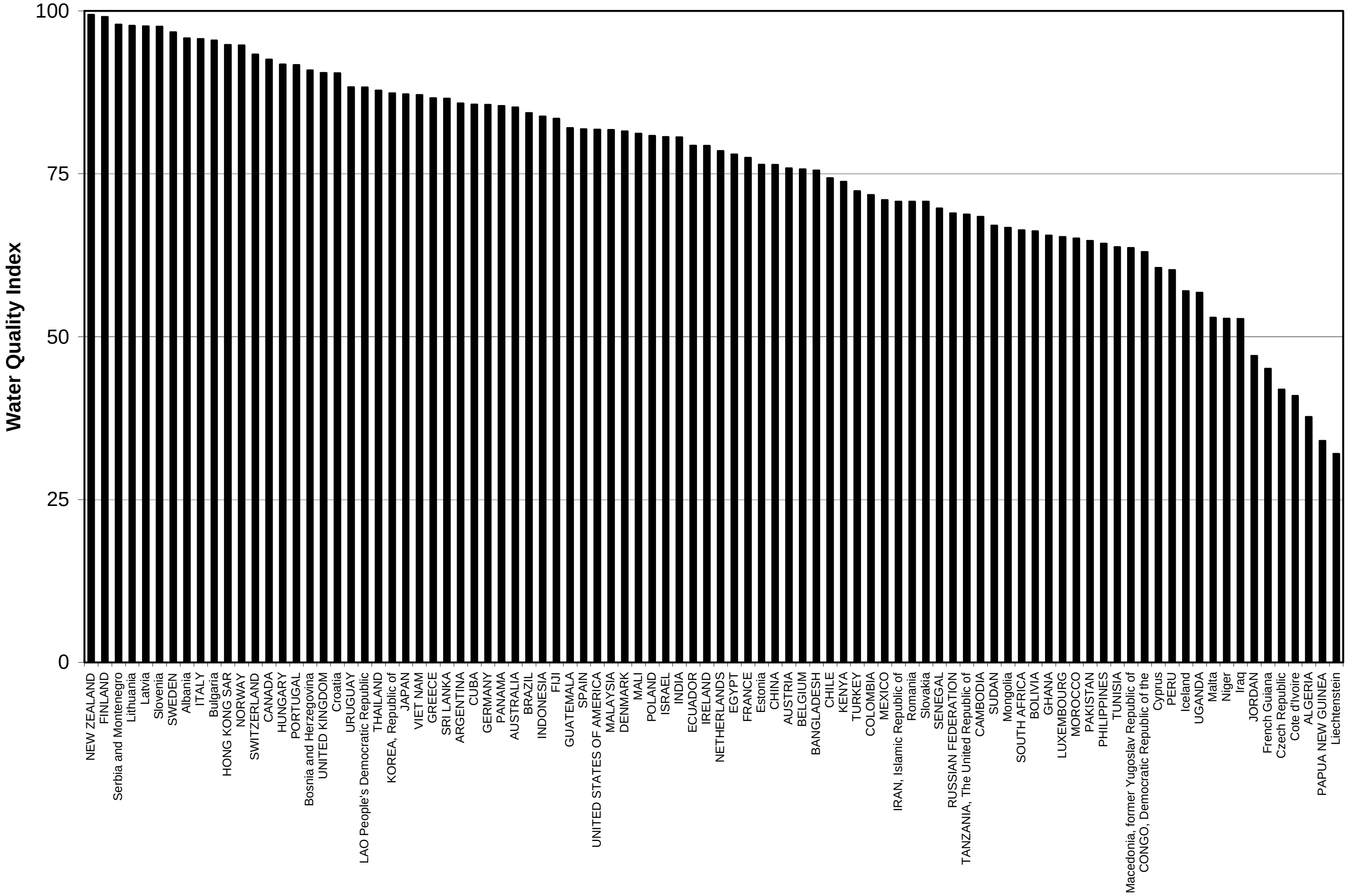

Figure 1. National water quality index rankings. A score of 100 indicates water quality targets were met for all five parameters.

Interpretation of the Water Quality Index

The WQI developed here is the most comprehensive picture of water quality, using real water quality monitoring data, available on a global scale to date. However, the index was built with imperfect data. Specifically, the five parameters included in the index were not universally reported by all countries, data were not necessarily current for all countries, and densities of monitoring stations were not the same among countries. Thus, while some countries reported water quality for only one or a few stations and for only one or a few of the five parameters, other countries reported water quality for their entire monitoring network and for all five parameters. The index was designed to adjust scores for some of the inconsistencies.

Station density and reporting inconsistencies

To evaluate the effect of these adjustments on the index, a comparison of the top and bottom five countries using different versions of the index was made (Table 2). The final version of the WQI, which includes a national scale adjustment for station density and includes only those stations that reported the most number of parameters in the country, ranks New Zealand, Finland, Serbia and Montenegro, Lithuania and Latvia in the top five countries globally. These rankings correspond exactly to the top 5 countries ranked when only stations that reported all five parameters were included in the index, following a station density adjustment. Note that by limiting the index to only stations that reported all five parameters, a WQI could only be computed for 68 countries. It was for this reason that the inclusion criteria were expanded to include the ‘best-reported’ stations from within a country.

The effect of limiting the inclusion of stations to those that were ‘best-reported’ is also evaluated: by including all stations for which any data were reported in the index, the top five countries in the revised WQI were New Zealand, Switzerland, Finland, Uruguay, and the People’s Democratic Republic of LAO, following a station density adjustment. New Zealand and Finland are the only two countries that were in the top five in both versions of the index. Serbia and Montenegro, Lithuania, and Latvia dropped to 11th, 26th, and 19th positions, respectively, due to the inclusion of between 78 and 97 river monitoring stations that previously were not included because they did not have the most complete parameter records available from their country.

Switzerland and Uruguay suffered most in their rankings due to the station density adjustment criteria. Whereas these two countries were in the top five whenever a station density adjustment was not applied, they did not rank in the top 5 following a station density adjustment in the final version of the index or in the reduced version of the index, where only the stations that reported all 5 parameters were included and country-level WQIs were computed for only 68 countries. In the case of both of these countries, all stations had all five parameters reported, and their uncorrected WQIs were high. However, the density of monitoring stations in these countries was comparatively low, which lowered their overall ranking once the national WQIs were adjusted for station density.

Table 2. Comparison of country rankings using different criteria to compute a national index. The entries in bold reflect the WQI in its final form.

Rank	Best-reported stations		Stations reporting 5 parameters only		All stations included	
	Station density adjustment applied	No station density adjustment	Station density adjustment applied	No station density adjustment	Station density adjustment applied	No station density adjustment
Top 5 countries						
1	**New Zealand**	New Zealand	New Zealand	New Zealand	New Zealand	New Zealand
2	**Finland**	Brazil	Finland	Brazil	Switzerland	Switzerland
3	**Serbia and Montenegro**	Finland	Serbia and Montenegro	Finland	Finland	Uruguay
4	**Lithuania**	Switzerland	Lithuania	Switzerland	Uruguay	LAO People's Democratic Republic
5	**Latvia**	Uruguay	Latvia	Uruguay	LAO People's Democratic Republic	Cuba
Bottom 5 countries						
88	**Czech Republic**	Cote d'Ivoire	Morocco	Morocco	Cote d'Ivoire	Czech Republic
89	**Cote d'Ivoire**	Czech Republic	Pakistan	Peru	Algeria	Papua New Guinea
90	**Algeria**	Papua New Guinea	Peru	Luxembourg	Papua New Guinea	Algeria
91	**Papua New Guinea**	Algeria	Uganda	Uganda	Denmark	Denmark
92	**Liechtenstein**	Liechtenstein	Jordan	Jordan	Liechtenstein	Liechtenstein

The different inclusion criteria had very little effect on the bottom five countries of the index. In its final version, the Czech Republic, Cote d'Ivoire, Algeria, Papua New Guinea and Liechtenstein ranked lowest in terms of their water quality. There was no change in the bottom five countries when the station density adjustment was removed, and only limited change when all stations within the country were included in the index (in this case, Denmark fell to second to last place from 40th position). Not surprisingly, the bottom five countries were quite different when the index was limited to only stations that reported all five parameters, so that a WQI could only be computed for 68 countries. This is because the WQI is computed as the average score for 5 reported parameters, even if fewer parameters were reported, and so countries that report all five parameters naturally would have higher WQIs (Figure 2).

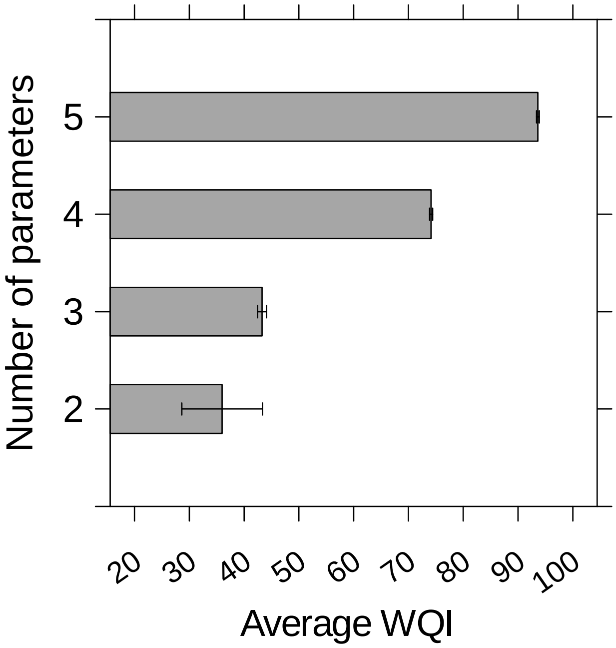

Figure 2. Relationship between the final version of the WQI and the number of parameters included. Data are mean country level WQIs. Error bars are standard errors.

The final version of the WQI was designed to balance the need for complete datasets with a need for increased country coverage in order to provide the most global picture possible for water quality. This necessarily involved making decisions and setting criteria for inclusion of data and penalties for under-reporting of water quality information. It would not be surprising to see many countries improve in their overall rankings, simply by reporting data for additional water quality parameters or by reporting data for a more comprehensive monitoring network. Countries that were not included in the index at all could be included in this global comparison simply by reporting water quality data to the UNEP GEMS/Water Programme.

Parameter contributions

The parameters included in the WQI were chosen because they are good indicators of common water quality problems (eutrophication, salinization, acidification, and organic pollution) and because they are commonly reported to international agencies such as the UNEP GEMS/Water Programme and the European Environment Agency. The majority of stations met the targets set for dissolved oxygen, pH, and conductivity, whereas more than half of the stations failed to meet nutrient targets set for the different forms of phosphorus and nitrogen (Table 3). Correlation of the proximity-to-target (PTT) scores for each parameter to the overall station WQIs provides insight into which parameters most heavily influenced the national WQI values (Table 3). Nitrogen, phosphorus and conductivity were most strongly correlated to station-level WQIs. pH was the only parameter where PTT scores were not significantly correlated to WQIs, and dissolved oxygen PTT scores were only very weakly correlated to WQIs.

Table 3. Summary proximity-to-target (PTT) scores for each parameter included in the water quality index (WQI) and their correlation to the overall station WQI. Asterisks denote significant correlations, such that ‘*’ = P < 0.05 and ‘**’ = P << 0.0001

	Mean (Standard deviation)	Median	Minimum	Maximum	N	% of stations failing to meet target	Pearson’s r
Dissolved oxygen	99.5 (0.9)	100	93.5	100	2018	39	-0.059*
pH	98.8 (7.6)	100	11.8	100	2052	6	-0.008
Conductivity	94.1 (15.6)	100	41.1	100	1553	18	0.511**
Nitrogen	82.1 (24.8)	93.1	3.7	100	2110	67	0.702**
Phosphorus	89.0 (22.2)	99.7	4.6	100	2092	51	0.590**
Station WQI	85.5 (16.5)	92.2	22.4	100	2127	90	1.00**

Nutrient pollution appears to be driving factor in the WQI, with nutrients having the highest correlation to the overall station WQI and the most number of stations that failed to meet targets. The targets used in the index were developed based on a compilation of scientific literature to reflect boundary concentrations between mesotrophic and eutrophic systems. There are currently no global targets for nutrients in inland waters, mostly because nutrients are not usually toxic to either aquatic organisms or humans, and natural background concentrations can vary by orders of magnitude depending on underlying geologies. Although site-specific targets could provide more reasonable estimates of true exceedances beyond natural background nutrient conditions, it remains likely that nutrient pollution would still be an important driving factor in the WQI. Eutrophication of aquatic environments is a global concern, as municipal, industrial and agricultural loadings of nitrogen and phosphorus continue to exceed natural loadings expected due to rainfall and runoff from the drainage basin (UNEP GEMS/Water 2006).

Dissolved oxygen was only weakly correlated to the WQI, despite a reasonably high exceedance rate (39%). The weak correlation is probably due to the fact that exceedances from the target concentrations were small compared to the magnitude of deviations from targets for parameters such as nitrogen and phosphorus. Thus, while PTT scores for nitrogen and phosphorus were as low as 3 and 4 out of 100, the minimum recorded PTT score for dissolved oxygen was 93.5, and the average score was 99.5 (Table 3). It is possible that more stringent targets for dissolved oxygen would yield a larger spread in PTT scores, but the targets derived here were based on the best available scientific information and a review of existing guidelines and standards for the protection of aquatic life.

The fact that only 6 % of monitoring stations failed to meet pH targets suggests that the targets chosen to reflect acceptable pH conditions were too broad, making the WQI insensitive to variations in pH. Given that different parts of the world are more sensitive than others to the effects of acid precipitation, primarily because of their underlying geology and the movement of atmospheric pollutants in their regions, it would make sense to set regional targets to better reflect natural background conditions in different parts of the world. This could improve the sensitivity of the WQI to pH, and better reflect the issue of acidification on a global basis.

Conductivity was quite highly correlated to the WQI but had a comparatively low rate of target exceedances on a station by station basis (18%, Table 3). There are two possible explanations for this trend. First, conductivity is often well-correlated to nutrient concentrations, suggesting that although conductivity may seldom fail to meet target concentrations, the patterns in its recorded values may mimic those observed for nutrients. In this case, PTT scores for nutrients and conductivity were significantly correlated (Pearson's correlation coefficient for conductivity to phosphorus and nitrogen were 0.26 and 0.30, respectively). The strength of the correlations between the raw conductivity and nutrient concentrations was higher than the PTT correlations ($0.26 \leq$ Pearsons' $r \leq 0.49$), but likely not high enough to explain the overall strong correlation of conductivity to the WQI.

The second possible explanation for the high correlation of conductivity to the WQI is the fact that conductivity was the least well-represented of the parameters included in the index, with only 73% of stations reporting conductivity compared to between 95 and 99 % reporting rates for the other parameters (Table 3). Analysis of variance of WQIs for stations that did and did not report conductivity revealed that approximately 45% of the variability in WQI was explained simply by the inclusion of conductivity in the index, and this value corresponds to a correlation coefficient of ~ 0.67, which is closer to the range of the linear correlation between WQI and conductivity PTT scores. Thus, it appears likely that the linear correlation detected between conductivity PTT scores and station level WQIs is due mostly to the presence or absence of conductivity in the index.

The observation that conductivity's presence or absence in the index could have a strong effect on WQI scores, leads to the question of whether it should be completely removed from the index because of under-reporting. A sensitivity analysis, where conductivity was removed from the index and a new WQI was computed as the average of 4 instead of 5 parameters, revealed that the reduced WQI was still significantly correlated to the original WQI (Pearson's $r = 0.86$). The strength of the correlation between the original WQI and the reduced WQI with conductivity removed was not as great as the correlations when other parameters were removed (correlation between WQI and reduced WQIs with dissolved oxygen, pH, nitrogen and phosphorus removed: $0.96 \leq$ Pearson's $r \leq 0.97$), but it was still significant. Had the removal of conductivity from the overall WQI yielded a non-significant correlation, strong justification would be provided for entirely removing conductivity from this version of the index because of its strong effect on index values, despite the fact that it seldom fails to meet targets. Thus, although the eventual removal of conductivity may be warranted in future versions of the WQI, unless better reporting of the metric is undertaken, its removal is not justified in this version.

Blueprint for future measurement

Although the index reported here provides a valuable snapshot of surface water quality for the 92 countries for which data were available, it can and needs to be improved upon. First, recent data from more countries and for all five parameters are required in order to better rank environmental performance as it relates to water quality on a global scale. The current formulation of the index could be improved upon by using only data from, say, the last three to five years of monitoring and ensuring that countries are well-represented in terms of station coverage. This would ensure that temporal trends in water quality conditions could eventually be tracked. The five parameters included in this index are very basic water quality monitoring parameters, and the targets against which concentrations were compared are necessarily general. Particularly in the case of nutrients and pH, regionally referenced nutrient targets may provide more specific information regarding the state of eutrophication of a country's surface waters.

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Appendix 1: Trophic status and nutrient enrichment of inland waters

The trophic status of a body of water is typically assessed according to its concentrations of total nitrogen and/or total phosphorus and how these relate to biological productivity. Water bodies are usually classified as being ultraoligotrophic, oligotrophic, mesotrophic, eutrophic or hypereutrophic systems, and these classes represent a gradient from low to high nutrient concentrations and biological productivity (Table A1).

Table A1. Nitrogen and phosphorus concentrations corresponding to intermediate (mesotrophic) to highly productive (hypereutrophic) trophic states in inland waters

Parameter	Mesotrophic	Eutrophic	Hypereutrophic	Type of water body	Source
Total Phosphorus (mg L^{-1})	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 (2001)
	0.010 – 0.030[a]	0.030 – 0.100[a]	> 0.100[a]	Lakes	Nurnberg (1996)
	0.010 – 0.020[a]	0.020 – 0.050[a]	0.050 - >0.100[a][*]	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 L^{-1})	0.350 – 0.650[a]	0.650 – 1.20[a]	> 1.20[a]	Lakes	Nurnberg (1996)
	0.753[b]	1.875[b]		Lakes and Reservoirs	Wetzel (2001)
	< 1.50[c]	≥ 1.50[c]			Dodds et al. 1998

[a] Data represent the range of expected concentrations
[b] Data represent the mean expected concentration
[c] Data represent the boundary concentration
[*] Includes a classification for 'supertrophic' as intermediate between eutrophic and hypereutrophic
[#] Ranking according to Figure 12, for global distribution of Total phosphorus

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Appendix 2: Station density adjustments to country-level water quality index scores.

Country-level water quality index scores were adjusted to account for the density of monitoring stations within the country. To avoid penalizing large, under-populated countries for low monitoring station densities, the number of monitoring stations in a country was divided by the populated land area (> 5 individuals km^{-2}) (CIESIN 2007). All monitoring stations in a country were included in determining density, regardless of whether they were included in the final water quality index. The target station density was set to reflect the standards originally recommended by the European Environment Agency's Monitoring and Information Network for Inland Water Resources (Nixon et al. 1998). Countries that failed to meet the target station density were penalized by adjusting their national WQI down by a factor of between 0.8 and 0.95, depending on the density of stations in their country (Table A2).

Table A2: Station density adjustments to national WQI scores:

Multiplier	1	0.95	0.90	0.85	0.80
Station density (/ 1000 km^2):	≥ 1 station	≥ 0.1 & < 1 station	≥ 0.01 & < 0.1 station	≥ 0.001 & < 0.01 station	< 0.001 station

** Station density determined per area of country where population density is > 5 people km-2, according to PLACE II dataset (CIESIN 2007).

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