Water Quality Index for Biodiversity
Technical Development Document

Prepared by

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Chapter 1: Introduction

The international community has committed “to achieve a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on earth by 2010.” This 2010 Target was formally adopted by governments at the 6th Conference of the Parties of the Convention on Biological Diversity in 2002, and endorsed later that year at the World Summit on Sustainable Development.

Water quality is important determinant of biodiversity in and around inland waters. Any number of water quality measurements can serve, and have already been used, as indicators of water quality and correlates of biodiversity. However, there is no single measure that can describe overall water quality for any one body of water, let alone at a global level. As such, composite indices are often calculated as they are able to quantify the extent to which a number of water quality measures deviate from normal, expected or ‘ideal’ concentrations. This method allows us to summarize complex data and compare water quality conditions across a range of inland water types.

Developing a Water Quality Index for Biodiversity can be used to track progress toward the 2010 Target in aquatic environments by quantifying the rate of change of water quality at monitoring stations. As water quality is directly correlated to biodiversity, a degradation of water quality can be expected to result in a loss of biodiversity.

The aim of this report is to outline the development of a composite index of water quality as it relates to biodiversity. Specifically, the report determines the parameters to be included in the index, the targets or benchmarks for each parameter in assessing biodiversity, the derivation of the index, followed by validation and sensitivity testing of the index. Preliminary interpretation of the index as it relates to tracking progress toward the 2010 Target of reducing the rate of loss of biodiversity is also undertaken.

What is water quality?

There are many different physical, chemical and biological parameters that can be used to measure water quality and therefore, there is no single 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.

Who monitors water quality?

The monitoring of inland water quality is a responsibility that can be shared among any number of agencies: federal, provincial, state or territorial, municipal or regional governments may all be responsible for monitoring, depending on the governance structure within a geopolitical region. Industries that discharge effluents into aquatic environments may have responsibility for monitoring the quality of the receiving environment. The general public, landowners, research agencies and non-governmental organizations may also take on the responsibility for monitoring water quality when they have a vested interest in its outcome.

At the international scale, the monitoring of water quality often depends on data submissions from national monitoring authorities to intergovernmental agencies. 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 3,000 monitoring stations include baseline (reference or non-impacted), trend (impacted) and flux (at the mouth of large rivers that discharge into the oceans) stations. Data in the GEMS/Water database date back to the 1960s.

While the GEMS/Water database is the most comprehensive global database of water quality, there are still gaps in country coverage. European countries report annual average water quality conditions for river, lake and groundwater monitoring stations to the European Environment Agency (EEA) and these data are available through the EEA web site. The EEA database includes monitoring data for over 5,000 rivers and lakes, with records dating as far back as the 1930s through to the present.

Composite Indices of Water Quality

Although there is no globally accepted composite index of water quality, some countries and regions have used, or are using, aggregated water quality data in the development of water quality indices. Most water quality indices rely on normalizing, or standardizing, data parameter by parameter according to expected concentrations and some interpretation of ‘good’ versus ‘bad’ concentrations. Parameters are often then weighted according to their perceived importance to overall water quality and the index is calculated as the weighted average of all observations of interest (e.g., Pesce and Wunderlin, 2000; Stambuk-Giljanovic, 1999; Sargaonkar and Deshpande, 2003; Liou *et al*., 2004; Tsegaye *et al*., 2006). Table 1 summarizes a number of key national and international indices that have been developed for water quality.

Table 1 Summary of indices developed that assess water quality either on a national or global level.

Index	Objective	Method	Use/distribution	Author
The Scatterscore index	Water quality	Assesses increases or decreases in parameters over time and/or space	Mining sites, USA	Kim and Cardone (2005)
The Wellbeing of Nations	Human and Ecosystem	Assesses human indices against ecosystem indices	Globally	Prescott-Allen, 2001
Environmental Performance Index	Environmental health and ecosystem vitality	Uses proximity-to-target measures for twenty five performance indicators tracked in six policy categories and combined into a final index score	Globally	Esty *et al.*, 2008
Index of River Water Quality	River health	Uses multiplicative aggregate function of standardized scores for a number of water quality parameters	Taiwan	Liou *et al*. (2004)
Overall Index of Pollution	River health	Assessment and classification of a number of water quality parameters by comparing observations against Indian standards and/or other accepted guidelines e.g. WHO	India	Sargaonkar and Deshpande (2003)
Chemical Water Quality Index	Lake basin	Assesses a number of water quality parameters by standardizing each observation to the maximum concentration for each parameter	USA	Tsegaye *et al*. (2006)
Water Quality Index for Freshwater Life	Inland waters	Assesses quality of water against guidelines for freshwater life	Canada	CCME (2001)

Similar to indices of economic strength, such as Gross National Product (GNP), these indices take information from a number of sources and combine them to develop an overall snapshot of the state of the national system. Even though there is considerable debate as to which measures should be included in the derivation of an index, and which information the index provides to the general public and to policy makers, there is some agreement that water quality indices are useful tools for comparing water quality across systems and over time. They can also provide a benchmark for evaluating successes and failures of management strategies aimed at improving water quality.

Chapter 2: Indicator development

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. These modifications have resulted in habitat loss, pollution, introduction of invasive species, and the manipulation of flows by the construction of dams and levees; all of these have ultimately led to losses of biodiversity. The loss is so great that the Convention on Biological Diversity (CBD) describes inland waters as one of the most threatened ecosystem types, and states 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 quality and establishing successful techniques in areas of improvement.

Parameter Selection

There are many different parameters that can be used to measure water quality. From a global perspective it is important to outline a few consistent measurements that can be measured easily, by all, on a regular basis, and that are clearly correlated to biodiversity in aquatic environments.

The specific parameters used to assess water quality were chosen based on findings reported in the primary literature. A literature review was conducted to determine which water quality parameters were most adequately reflective of aquatic biodiversity in both temperate and tropical rivers and lakes.

Many studies have shown a strong relationship between a number of key water quality parameters and biodiversity measures in both invertebrate and vertebrate species. For example, a study conducted in the Damas River Hydrographic Basin using macroinvertebrates as indicators found that a number of parameters were significantly related to biodiversity (Figueroa *et al.*, 2003). Results revealed a negative relationship between Families Biotic Index (FBI) and dissolved oxygen (r^2=0.53). The FBI was inversely related to species richness, i.e., it was a measure of deteriorating biodiversity. They also observed a positive relationship between the FBI and conductivity (r^2=0.50) total phosphorus (r^2=0.71), temperature (r^2=0.66), nitrite (r^2=0.56), BOD (r^2=0.46) and total nitrogen (r^2=0.46).

In a study assessing macroinvertebrate diversity and abundance in urban streams in Manaus, Amazonas, Brazil, dissolved oxygen and species abundance were found to be positively correlated (r^2=0.76) (Couceiro *et al.*, 2007). Canonical correspondence analysis also identified that streams with few macroinvertebrate taxa were associated with high values of conductivity as well as temperature, pH and nutrients (nitrogen and phosphorus). They concluded that reduced taxon richness was closely associated with elevated nutrients in these areas.

Dyer *et al.* (2003) conducted a study looking at the influence of untreated wastewater to aquatic communities (algae, invertebrates and fish) in the Balatuin River, The Philippines. Taxon richness and abundance of macroinvertebrates were influenced by wastewater discharge. Specifically, decreased DO and increased BOD were associated with the wastewater discharge and sites dominated by pollution-tolerant species, e.g., oligochaete worms and chironomids. Ammonia was also identified as a causal factor of poor colonization and recovery of species in areas affected by the discharge. In an earlier study, Dyer *et al*. (2000) also identified ammonia as a negative, moderating factor for an index of biotic integrity and fish taxa richness in a study of fish communities within the state of Ohio, USA.

Azrina *et al.* (2006) measured macroinvertebrate richness and diversity indices along the Langat River, Malaysia to assess the influence of anthropogenic impacts on biodiversity. They found that both richness and diversity indices were generally influenced by conductivity, temperature and total suspended solids.

Pathiratne and Weerasundara (2004) looked at organic pollution status in three inland water bodies in Sri Lanka. They found that benthic oligochaete species richness and abundance were consistently higher in the highly eutrophic and organically polluted Lake Beira. Oligochaetes are used to assess organic pollution and trophic status, an increase in richness and abundance is indicative of organic pollution. They found that the structure of the oligochaete communities was influenced by conductivity, nitrate and BOD.

Growns *et al.* (1992) assessed macroinvertebrates, zooplankton and water quality variables in wetlands near Perth, Australia. They found that in the most nutrient enriched wetlands species richness decreased and numbers of tolerant species increased. In a study assessing Odonata distribution in a lowland river catchment in eastern England, phosphate concentrations, BOD and low velocity were found to influence larval assemblages (Hoffmann and Mason, 2005). Adult populations were found to respond indirectly to BOD and ammonia concentrations.

Nutrient enrichment and its effects on periphytic communities were assessed by Marcus (1980). The study found that nitrogen concentration was the only stream physiochemical parameter which correlated with periphytic variations. It was suggested that ammonia was the primary factor influencing periphytic growth. The distribution of epilithic diatoms in the Nairobi River, Kenya were assessed with regards to environmental conditions (Ndiritu *et al.*, 2006). It was found that diatom assemblages responded to concentrations of nitrate, nitrite, phosphate, conductivity, TDS, alkalinity and temperature. Diatom richness was also found to be significantly related to temperature, altitude, BOD, conductivity, calcium, alkalinity, organic nitrogen and phosphorus in a study conducted in the LaTrobe River, Australia (Chessman, 1986).

Baldigo and Lawrence (2000) investigated the direct effects of acidification on fish community composition in the Neversink River, New York. They found that species richness and total density of fish were adversely affected at strongly to severely acidified sites. Regression analysis revealed that pH, along with Ca^{2+}, Al, K^+ and temperature accounted for 75 to 80% of variability in species richness; pH having a positive relationship ($r = 0.86$). They concluded that species distributions and species richness were most strongly affected by stream acidification.

A number of water quality variables were also found to be correlated with macroinvertebrate species richness and abundance in a study conducted in farm dams in New South Wales, Australia (Brainwood and Burgin, 2006). Conductivity was one of the most closely correlated water quality variables related to community composition. Townsend *et al.* (1983) assessed the influence of physical and chemical factors on invertebrate and fish community structures in streams in Southern England. They found that the structure of communities was strongly related to variation in stream pH, temperature and stream discharge; where acidified sites had low species richness (r^2=0.73).

Rundle and Hildrew (1990) studied the distribution of micro-arthropods in streams in southern England, assessing the importance of a number of physical and chemical variables in determining both the distribution of micro-arthropod taxa and community structure. Micro-arthropod species richness and densities were decreased in acidic sites. Significant positive correlations were observed between pH and species richness of total micro-arthropods (r=0.644), Hydrachnellae (r=0.528), Harpacticoida (r=0.637), and Cladocera (r=0.457). Multivariate analysis also showed that annual mean temperature, conductivity and maximum discharge were important factors in explaining species composition between sites.

These studies clearly show a strong relationship between a number of key water quality parameters and biodiversity measures in both invertebrate and vertebrate species. The predominant parameters showing strong consistent correlations were pH, temperature, dissolved oxygen, nutrients (nitrogen and phosphorus) and conductivity. These primary parameters are outlined in Table 2. Variations of parameters are included within some of these categories as they have demonstrated strong relationships; for example, nitrate, nitrite and ammonia are listed under nitrogen, phosphates and dissolved inorganic phosphorus are listed under phosphorus and salinity and TDS are listed under conductivity. In addition to these a number of other parameters also demonstrated significant relationships to some measure of biodiversity but were not included in this list either because a) there were only one or two studies demonstrating the relationship or b) they were strongly related to parameters already selected, e.g., alkalinity (pH) and biochemical oxygen demand (dissolved oxygen).

Table 2 Summary table of selected parameters, references and countries where the study was conducted.

Parameter	Reference	Study area
Conductivity	Azrina et al. 2006	Malaysia
	Brainwood and Burgin 2006	Australia
	Chessman 1986	Australia
	Clements et al. 2000	Colorado
	Couceiro et al. 2007	Brazil
	Dauer 1993	Chesapeake Bay
	Figueroa et al. 2003	Chile
	Frisch et al. 2006	Spain
	Growns et al. 1992	Australia
	Nather Khan 1991	Malaysia
	Ndiritu et al. 2006	Kenya
	Pathiratne & Weerasundara 2004	Sri Lanka
	Reash and Pigg 1990	Oklahoma
	Rundle and Hildrew 1990	England
	Walsh et al. 2001	Australia
DO	Boulton et al 1997	New Zealand
	Couceiro et al. 2007	Brazil
	Dauer 1993	Chesapeake Bay
	Dauer et al. 1992	Chesapeake Bay
	Dyer et al. 2003	Philippines
	Figueroa et al. 2003	Chile
	Killgore and Hoover 2001	Arkansas
	Martin et al. 2000	India
	Reash and Pigg 1990	Oklahoma
Nitrogen	Chessman 1986	Australia
	Clements et al. 2000	Colorado
	Couceiro et al. 2007	Brazil
	Dyer et al. 2000	USA: Ohio
	Dyer et al. 2003	Philippines
	Figueroa et al. 2003	Chile
	Growns et al. 1992	Australia
	Hofmann & Mason 2005	UK
	Ibarra et al 2005	France
	Marcus 2007	Montana
	Nather Khan 1991	Malaysia
	Ndiritu et al. 2006	Kenya
	Pathiratne & Weerasundara 2004	Sri Lanka
	Singkran and Sudara 2005	Thailand
pH	Baldigo and Lawrence 2000	New York
	Clements et al. 2000	Colorado
	Conlon et al. 1992	Canada
	Couceiro et al. 2007	Brazil
	Doka et al. 2003	Canada
	Fryer 1980	England
	Nyberg 1998	Sweden
	Rundle and Hildrew 1990	England
	Townsend et al. 1983	England
	Chessman 1986	Australia
	Clements et al. 2000	Colorado
	Couceiro et al. 2007	Brazil

Parameter	Reference	Study area
Phosphorus	Figueroa et al. 2003	Chile
	Growns et al. 1992	Australia
	Hofmann & Mason 2005	UK
	Ibarra et al 2005	France
	Ndiritu et al. 2006	Kenya
	Singkran and Sudara 2005	Thailand
Water temperature	Azrina et al. 2006	Malaysia
	Baldigo and Lawrence 2000	New York
	Chessman 1986	Australia
	Clements et al. 2000	Colorado
	Figueroa et al. 2003	Chile
	Reash and Pigg 1990	Oklahoma
	Townsend et al. 1983	England

The choice of parameters to be included in the computation of a composite index of water quality was based on 1) the presence of a relationship between the water quality parameter and biodiversity and 2) the availability of monitoring data for the parameter in international water quality monitoring databases such as UNEP GEMS/Water's GEMStat database and the European Environment Agency's WaterBase database. With these two factors in mind, the following parameters were chosen for inclusion within the WQIB:

Dissolved Oxygen
Electrical Conductivity
pH
Temperature
Nitrogen
Phosphorus

Beyond being good correlates of biodiversity, the parameters chosen for the development of a water quality index for biodiversity were selected for an additional reasons, that is, they are good indicators of specific issues that are relevant on a global basis (eutrophication, nutrient pollution, acidification, salinization, climate change).

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's 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 biological 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 3.

Table 3 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 – 8.5	pH must fall within target range
Conductivity	500 µS cm^{-1}	Conductivity must not exceed target
Total Nitrogen	1 mg L^{-1}	Total nitrogen must not exceed target
Total Phosphorus	0.05 mg L^{-1}	Total phosphorus must not exceed target
Temperature	Latitude dependent	Temperature must not exceed modeled temperature

Temperature target

The identification of a general target for water temperature is difficult because natural variations occur with climate and season. However, increases in temperatures that may occur due to climate change have the potential to result in shifts in species composition and loss of endemic species.

Relationships between latitude and mean summer water temperature were used to compute a guideline for water temperature. Summer temperature data from the GEMStat database were used to assess trends by latitude. Summer averages were calculated for May to October at Latitudes 0 and above (northern hemisphere) and November to April at latitudes 0 and below (southern hemisphere). The summer averages for the years 2000 to 2007 were plotted by latitude (**Error! Reference source not found.**). A polynomial relationship best described the relationship (r^2 = 0.76, Residual variance = 10.1, n = 1619). Temperature values that exceeded the 95% confidence limit of the predicted summer average temperature for a station were considered to be in exceedance of the target temperature for that station (Figure 2).

Using this technique it was possible to 1) calculate a 95% confidence interval to determine an appropriate upper guideline for average temperatures for those stations that had temperature monitoring data, and 2) determine a predicted temperature for stations lacking real data which was used to calculate a dissolved oxygen guideline (see text for dissolved oxygen targets).

a)

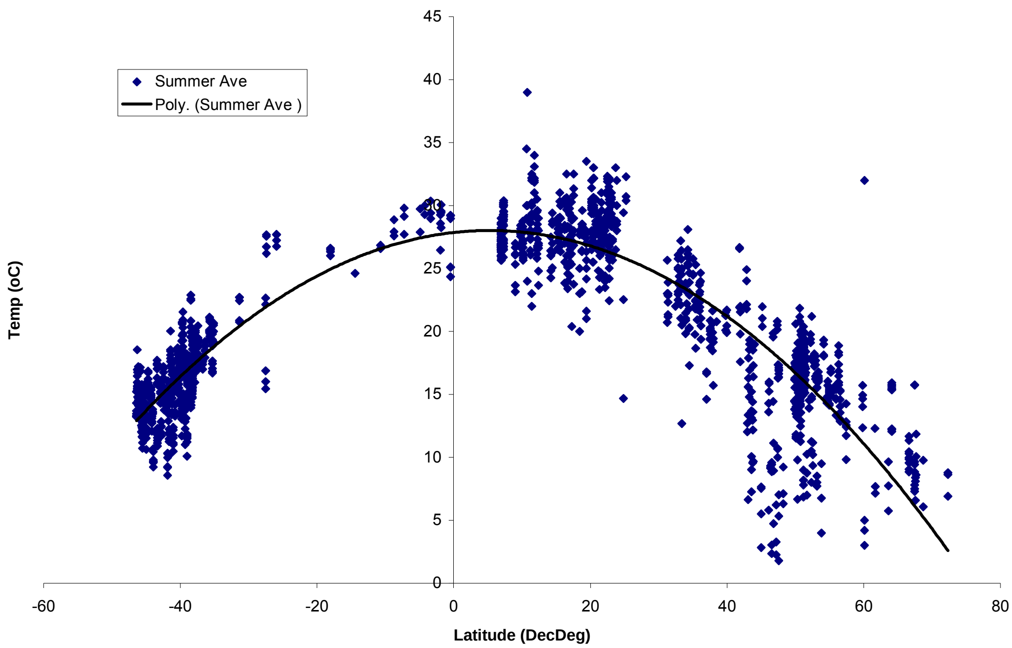


Figure 1 Global summer temperatures between 2000 and 2007 recorded within GEMStat as a function of latitude expressed in decimal degrees. Fitted line is polynomial curve (Temperature = 27.9 + 0.060 · (latitude) – 0.060 · (latitude)^2; r^2 = 0.76, n = 1619, residual variance = 10.1).

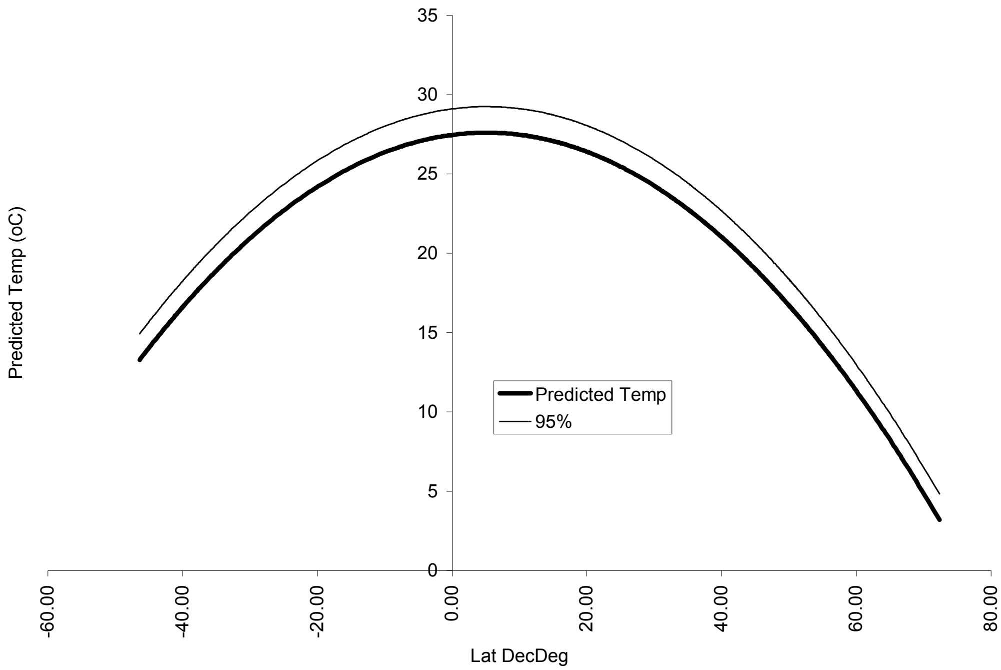


Figure 2 Predicted temperatures (^{o}C) and calculated 95% confidence interval based on latitude (decimal degrees) using global data from the UNEP GEMS/Water Programme. Predicted temperature based on polynomial equation (Temperature = 27.9 + 0.060 · (latitude) – 0.060 · (latitude)^2; $r^2 = 0.76$, n = 1619, residual variance = 10.1).

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).

Dissolved oxygen targets were assigned on a station by station basis, based on their predicted summer average temperature (Figure 2). A guideline of 6 mg L^{-1} was applied to those stations whose predicted summer average temperature was greater than or equal to 20 ^{o}C. A guideline of 9.5 mg L^{-1} was applied to those stations whose predicted summer average temperature was below 20 ^{o}C.

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 8.5.

Conductivity target

The mean salinity of the worlds rivers is approximately 120 mg L^{-1} total dissolved solids (TDS) which corresponds to an electrical conductivity of approximately 220 µS cm^{-1} (Weber-Scannell and Duffy, 2007). 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 TDS 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 targets

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 2001). 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 (Table 4).

Table 4 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

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). However, generally strong relationships exist between annual average total and dissolved concentrations of both nitrogen and phosphorus, making it possible to predict average total concentrations based on average dissolved concentrations (Table 5). In cases where dissolved forms of nitrogen or phosphorus were reported instead of total forms, the total form was imputed based on the dissolved concentrations. A total of 27% and 6% of the nitrogen records were imputed based on dissolved inorganic nitrogen and NO_3+NO_2, respectively, whereas 18% and 1% of the phosphorus records were imputed based on orthophosphate and total dissolved phosphorus, respectively.

Table 5 Regression models predicting total nitrogen and phosphorus based on dissolved forms of the same nutrient. To reduce the effect of extreme outliers on model results, linear models were developed by excluding values that were greater than the 95[th] percentile of both the dependent and independent variables.

Nutrient (total number of records with real data)	Model	Model r^2	Residual variance	N to build model	Number of records where Total N was

					imputed
Total nitrogen (43,791)	0.475 + 1.136 × (Dissolved inorganic nitrogen)	0.89	0.352	27,616	17,850
	0.615 + 1.206 × (NO_3+NO_2)	0.79	0.703	23,227	4,223
Total phosphorus (52,208)	0.035 + 1.308 × (Orthophosphate)	0.71	0.0035	39,457	11,767
	0.0233 + 1.1833 × (Total Dissolved phosphorus)	0.64	0.0035	374	545

Index Calculation

The water quality index for biodiversity (WQIB) is a proximity-to-target (PTT) index computed on a station by station basis using measurements of the parameters as outlined above (temperature, dissolved oxygen, pH, electrical conductivity, total nitrogen, and total phosphorus). PTT scores for each parameter were derived from exceedances of annual average concentrations from targets, following winsorization of the exceedance data at the upper 95th percentile. PTT was calculated as the difference between observed values and the target divided by the range between the worst observed value and the target. PTT scores ranged from 100 (targets met) to 0 (most extreme failure to meet targets). The WQIB was computed as the average of PTT scores for the variables reported at a station in one year. A WQIB of 100 indicates that targets for all of the parameters measured at a station and year were met; increasing distance away from a perfect score indicates progressive deterioration of water quality.

The WQIB was computed for a total of 73,657 records, with data from 6,216 stations from 88 countries from each of the world's continents except Antarctica. The index computations range from 1931 to 2007. The average time span and number of years of data for the entire set is 12 years; some stations have as many as 55 years of data, spanning up to a 74 year time period. The average number of parameters included in the index is 3.7, with a median of 4, indicating that two thirds of the parameters chosen for the index computation were included at least half of the time.

WQIB scores ranged from 0 to 100, and averaged 83.3 with a median of 90.9 (Table 6). Nitrogen and phosphorus were the variables that most often failed to meet targets, and the nutrient PTT scores were the most strongly correlated to the WQIB. Temperature was least often reported in the available data sets: this is mostly because temperature is not a variable that is a part of the European Environment Agency's dataset.

Table 6 Summary of proximity to target (PTT) scores for each parameter included in the Water Quality Index for Biodiversity and their correlation to the overall WQIB. All correlations are significant (P << 0.0001).

	Mean (standard deviation)	Median	N	% of records failing to meet target	Pearson's r

Conductivity	91.6 (25.1)	100	23,995	13.6	0.59
Nitrogen	76.4 (31.7)	92.8	65,874	61.3	0.77
Oxygen	85.6 (28.6)	100	53,184	31.1	0.62
pH	92.3 (24.5)	100	54,327	12.2	0.25
Phosphorus	81.1 (29.5)	95.9	64,520	59.7	0.81
Temperature	85.0 (29.0)	100	7,921	31.2	0.46
WQIB	83.3 (20.5)	90.9	73,657	76.2	1.00

To aid regional interpretation of the WQIB, scores were divided into classes of Excellent (WQIB = 100), Good (95 ≤ WQIB < 100), Fair (90 ≤ WQIB < 95), Marginal (75 ≤ WQIB < 90) and Poor (WQIB < 75).

Chapter 3: Sensitivity analysis

The sensitivity of the index to the chemical and physical parameters included was tested by removing each parameter and then recalculating a reduced index. Correlations between the WQIB and the reduced indices were then examined. A lack of correlation between the original WQIB and the reduced index would imply that the WQIB was highly sensitive to the inclusion of that parameter in the index.

Although the reduced models were all highly correlated to the original WQIB, the removal of nitrogen had the greatest effect on WQIB with a correlation coefficient of 0.92 (Table 7). The removal of temperature from the index computation had the smallest effect on WQIB scores (Pearson's r = 0.99), probably because there were so few temperature records compared to other parameters (only ~ 11% of all of the WQIB computations had records for temperature). The effect of removal of conductivity on the WQIB also was relatively small (Pearson's r = 0.98) and resulted in an increase in mean index scores, and this is likely due to the fact that comparatively few records failed to meet targets of conductivity and also because only about one third of all of the WQIB scores included a measure for conductivity. The removal of pH from the index had an effect that was comparable to the removal of phosphorus (Pearson's r = 0.94); the removal of pH resulted in a drop in mean index scores whereas the removal of phosphorus resulted in an increase in mean index scores. The removal of oxygen also resulted in a drop in mean index scores.

Table 7 Sensitivity of Water Quality Index for Biodiversity to removal of different parameters from index computation. Correlation coefficients are for the relationship between the WQIB and a recomputed WQIB with removal of the parameter as indicated. All correlations are significant ($P << 0.0001$). Arrows indicate an increase (↑) or decrease (↓) in mean index value following removal of the parameter and recalculation of the index. N is the number of records in reduced models.

Reduced model	Pearson's r	Effect on mean index value	N
Conductivity removed	0.98	↓	73,587
Nitrogen removed	0.92	↑	73,046
Oxygen removed	0.95	↓	73,013
pH removed	0.94	↓	72,564
Phosphorus removed	0.94	↑	72,546
Temperature removed	0.99	↑	73,625

The WQIB was sensitive to the number of parameters included in index computation. Significant differences in mean index scores were detected among models that were computed based on between 1 and 6 parameters ($P < 0.0001$, analysis of variance). However, the effect was small and explained only 2.1% of the variability in index scores. There was a generally positive effect of reporting more parameters, as WQIB scores were higher when 4 to 6 parameters were reported than when 3 or fewer parameters were reported (Figure 3).

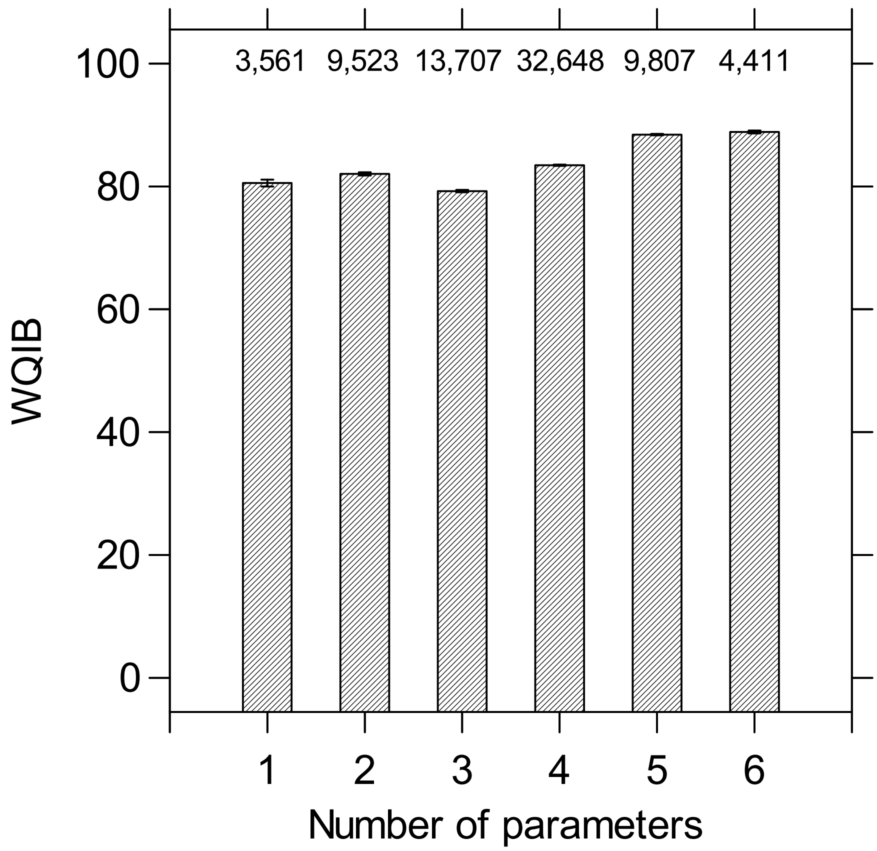


Figure 3 Relationship between number of parameters reported and the WQIB score. Data are mean ± 1 standard error. Numbers at the top of the figure correspond to the number of cases in each category.

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.

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.

Chapter 4: Index Validation

Case-study: Orange River drainage basin, South Africa

The Orange River basin is situated within the South Africa Ecoregion 575 Southern Temperate Highveld and is classed under the temperate upland rivers major habitat type. Between 1990 and 2007 the proportion of stations within this ecoregion classified as Excellent – Good were between 40 and 60% (Figure 4). The proportion of stations classified as poor were approximately 20-30%. The number of stations recording a WQIB within this ecoregion ranged between 9 and 15. Overall, the proportion of stations within each classification has been variable since 1990. However, over the last five years there has been a steady increase in stations classified as excellent to good and, up until 2006, a steady drop in stations classified as poor. This suggests that water quality within this ecoregion is improving.

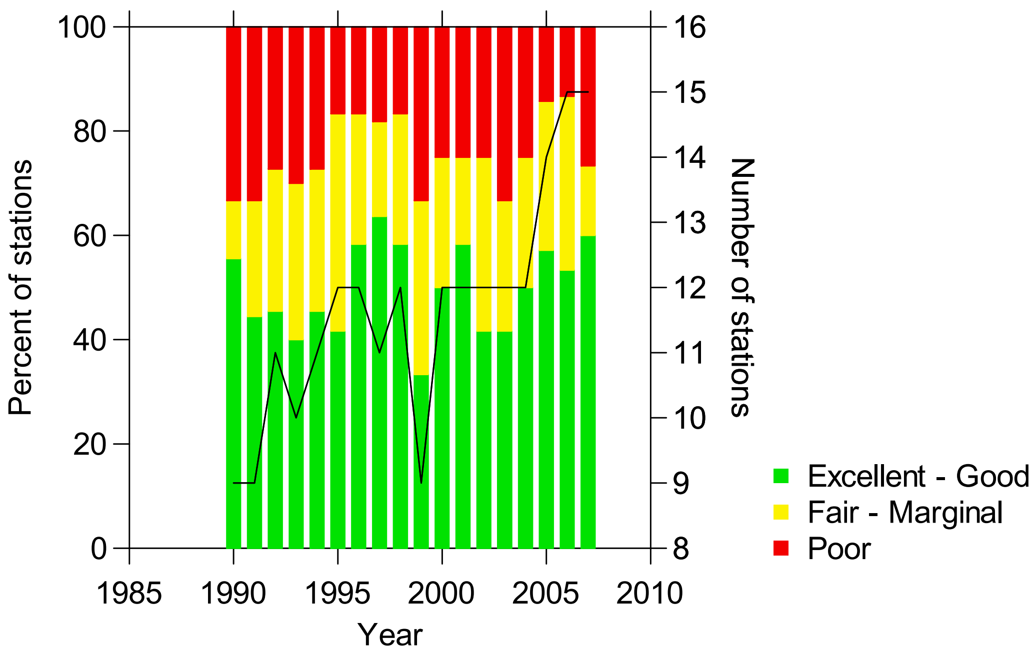


Figure 4 Trends in water quality index for biodiversity (WQIB) in the South African Southern Temperate Highveld freshwater ecoregion. Bars are the percentage of excellent-good, fair-marginal and poor WQIB scores by year. Black line represents the number of stations reporting in each year.

To assess whether a similar pattern was observed at a river basin scale, a validation study was conducted on the Orange River Basin, specifically using the Vaal and Orange Rivers.

Introduction

The Orange and Vaal Rivers are the two largest rivers in South Africa. Originating from the Drakensburg Mountains they both flow westwards towards the Atlantic Ocean (Figure 5). The Vaal River supports 37% of the country's economic activity and has the largest water demand (total system demand of approximately 3,000 million m^3/annum). The major anthropogenic impacts on the Vaal River are derived from industrial effluents, domestic and commercial sewage, acid mine drainage and agricultural run-off (van Vuuren and Pieterse, 2005). Previous studies have identified that the best water quality in the Vaal River is located at the Vaal Dam (upstream) and that water quality deteriorates as it flows downstream towards the Orange River due to industrial inputs from the Witwatersrand region.

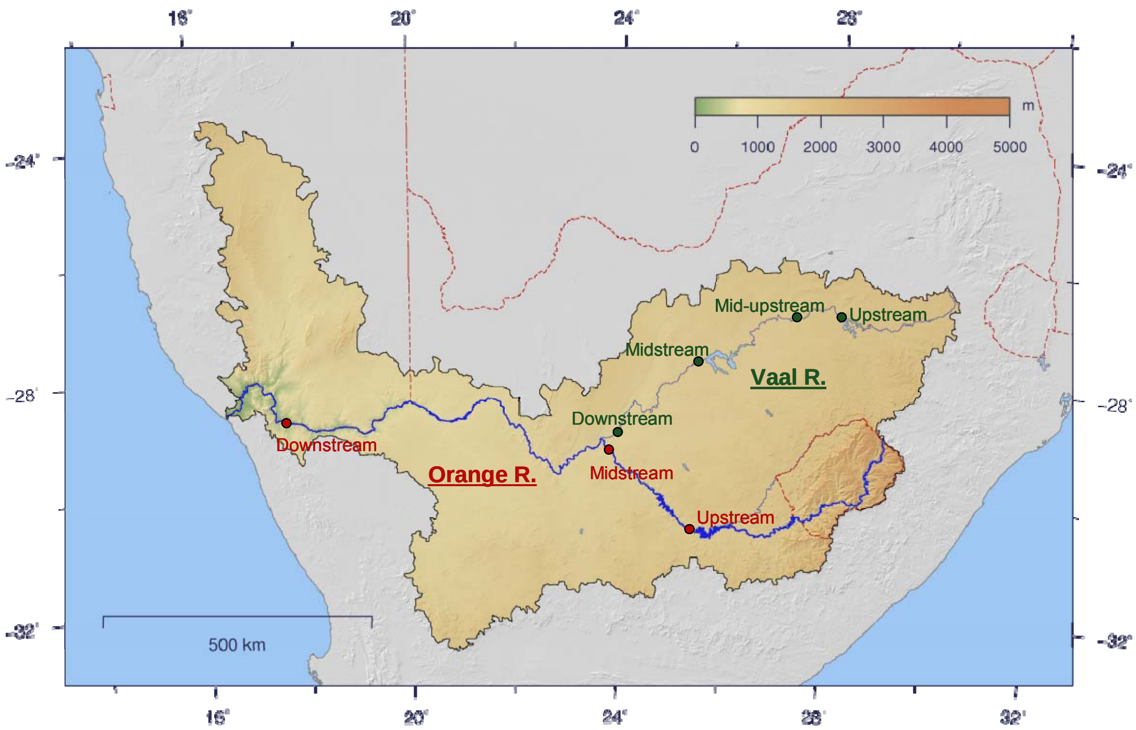


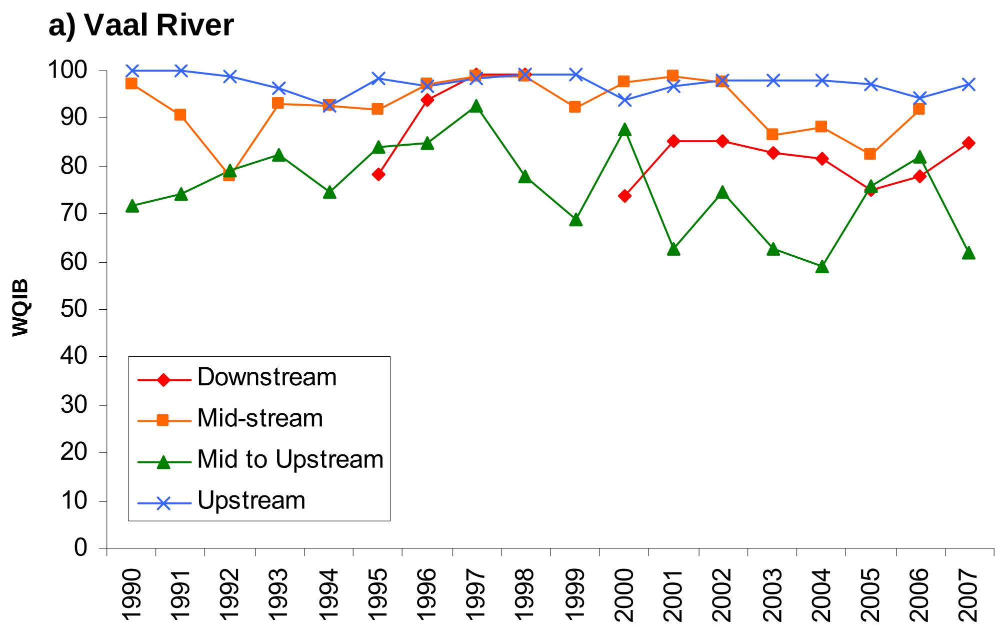
Figure 5 Orange River drainage basin, South Africa. Location of UNEP GEMS/Water monitoring stations along the Orange and Vaal Rivers are indicated in red and green, respectively.

Patterns in WQIB in Vaal and Orange Rivers

The WQIB scores for monitoring stations in both the Orange and Vaal rivers were plotted over time (Figure 6 a & b). The highest WQIB scores in the Vaal River were detected at the upstream site, located at the Vaal Dam (038018). The Vaal Dam was originally designed to serve the reef complex and provide water to the Vaal/Harts irrigation scheme. It is currently being used for domestic and industrial water supplies. Water quality in the Vaal River was poorer at the mid to upstream site (038004) which is located just south and downstream of Johannesburg (Figure 4a). The deteriorating water quality was not surprising as this particular site reflects the impact of major industrial complexes and mining activities in the upstream catchment of the Vaal River system. Water quality at the mid-stream site (Bloemhof Dam: 038019) was comparable to the most upstream site in the Vaal River. Bloemhof Dam plays an important role in relieving the pressure on the Vaal Dam. The main purpose of the dam is to store and regulate water for irrigation purposes downstream. Deterioration in water quality was again noted at the downstream Vaal River site (038003), but not to the same level as that observed in the mid to upstream site. A gradual drop in water quality was evident at the downstream site between 2000 and 2005, with evidence of some improvement after 2005. A similar temporal pattern after 2000 was also observed in the mid-stream site. Water quality in the upstream site at the Vaal Dam has been consistently good since 1990.

The three sites along the Orange River were very similar in both spatial and temporal trend (Figure 6b). The overall WQIB was good to excellent for all three sites from 1990 to 2007.

Because the Orange River demonstrated such a consistent pattern in WQIB scores, the validation study focused on the Vaal River which demonstrated a variable pattern both spatially and temporally.



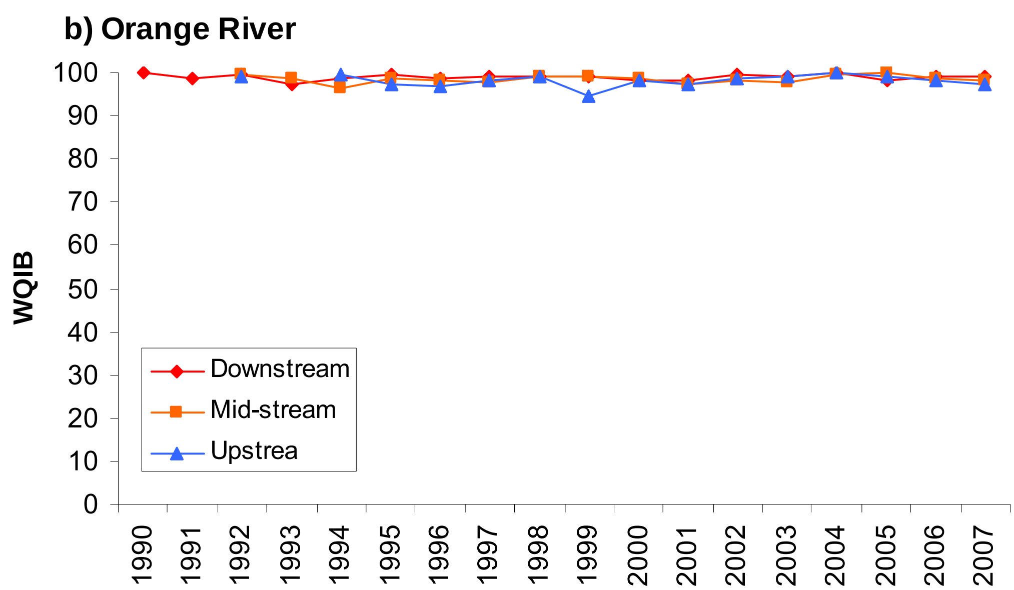


Figure 6 Temporal trends in WQIB from 1990 to 2007 at various points in the a) Vaal river and b) Orange River, South Africa.

Parameter contributions

The Vaal River is an important source of water for the Witwatersrand region. This region is one of the world's richest gold-mining areas and although many of the older mines are now nearly exhausted, it still produces most of South Africa's gold and much of the total world output. There are many other industries within the Witwatersrand region, such as engineering, steel milling, metallurgy, machine building, diamond cutting, food processing, and the manufacture of chemicals, cement, furniture, and clothing.

Spatially, WQIB scores indicated that water quality decreased around two main areas of the Vaal River: the mid to upstream site (038004) and the downstream site (038003). Temporally, the WQIB scores were quite variable; however, at the two sites (038003 and 038004) with the lowest scores, there was a downward trend in the WQIB from 1997 onward. The objective of this validation study was, firstly, to determine which parameters are causing the WQIB to deteriorate both spatially and temporally, and, secondly to understand the possible causes of this deterioration.

Validation analysis was conducted by comparing the water quality monitoring data from GEMStat that were used to calculate the index to the respective index scores at each station and over time.

Assessment of the parameters was conducted on a site-by-site basis. Following identification of the parameters, correlation analysis of the parameters against the index value was conducted for each station over time. The following analysis was divided into individual sites: 1) Upstream (038018), 2) Mid to upstream (038004), 3) Midstream (038019) and 4) Downstream (038003).

For all four sites along the Vaal River, the three main parameters that were consistently in exceedance were nitrogen, phosphorus, and electrical conductivity. pH was also measured at each site but did not exceed guidelines during the study period. Concentrations of each parameter were plotted against the WQIB to visually assess the relationship (Figure 7 - Figure 10). In addition, Pearson's correlation analysis was conducted to assess whether the relationship was statistically significant (Table 8). The analysis has been split by site, a detailed description of the results by site follows:

1) Upstream – Vaal Dam (038018)

   The upstream site had the best water quality compared to the other three. This is not surprising considering this site is situated quite close to the source of water for the Vaal and sources of contaminants upstream of this site are few. This is reflected in the parameter contributions where exceedances are rare and very small when they do occur. Interestingly, the only parameters to exceed were nitrogen and phosphorus (Figure 7). Correlation analysis revealed a negative relationship between both nitrogen and phosphorus and the WQIB (r=-0.93 and r=-0.68 respectively; Table 8).

2) Mid to upstream (038004)

   WQIB dropped substantially at the mid to upstream with exceedances in electrical conductivity, nitrogen and phosphorus. This site is located just south of Johannesburg and is influenced heavily by both urban and industrial development. Pearson's correlation analysis revealed that phosphorus and conductivity were significantly negatively correlated to WQIB (r=-0.67 and r=-0.77 respectively). Interestingly nitrogen was positively correlated with WQIB (r=0.68; Table 8). Temporally, the WQIB was quite variable at this site. This variability may be due to changes in flow, specifically because of the changes in electrical conductivity. Phosphorus showed a steady increase over time at this site and on the whole the water quality did not improve over time (Figure 8). Further analysis of dilution effects and the relationship to river flow will follow this section.

3) Midstream (038019)

This station is located at the Vaal Dam. WQIB improved at this site with only nitrogen continually in exceedance and conductivity and phosphorus only exceeding some of the time. Temporally, the water quality was consistently good and similar to the upstream site. Nitrogen concentrations dropped over time and phosphorus concentrations were below targets except for a peak in 2006 (Figure 9). Correlation analysis revealed that conductivity had the strongest relationship with WQIB (r=-0.66, Table 8).

4) Downstream (0380003)

Despite a lack of data for some years at this site, we can see that the WQIB dropped slightly compared to the midstream site. Temporally, the WQIB deteriorated over time with the lowest index value recorded in 2005-06 and the highest recorded in 1995-96. Conductivity and phosphorus were continually in exceedance with nitrogen only exceeding some of the time. This site is located just upstream of where the Vaal meets the Orange River (Figure 5). The drop in WQIB in the last 5 years seems to predominantly be due to conductivity (Figure 10). Similar to the midstream site correlation analysis revealed that conductivity demonstrated the strongest relationship to WQIB (r=-0.83, Table 8).

Table 8 Pearson's correlation coefficients comparing WQIB scores to mean annual values of water quality monitoring data at four sites along the Vaal River. Asterisks denote significant correlations such that *: $P \leq 0.05$, **: $P \leq 0.01$, and ***: $P \leq 0.001$. Values in brackets denote sample size of correlation.

	Downstream	Midstream	Mid to upstream	Upstream
Electrical conductivity	-0.83** (12)	-0.66* (17)	-0.77** (18)	0.45 (18)
Phosphorus	0.14 (12)	-0.40 (17)	-0.67* (18)	-0.93*** (18)
Nitrogen	0.45 (11)	-0.41 (16)	0.68* (17)	-0.68* (17)

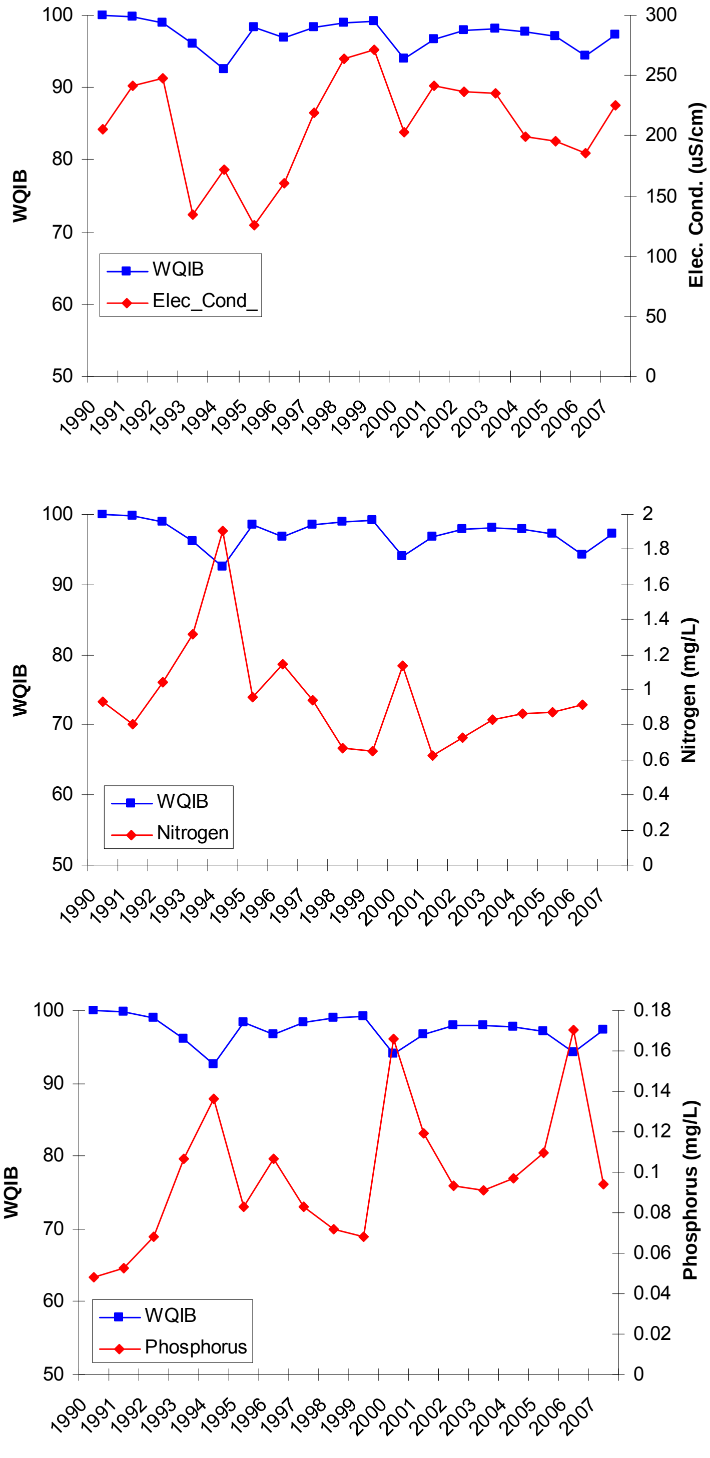


Figure 7 Water quality index for biodiversity (WQIB) scores and mean annual concentrations of electrical conductivity (top panel), nitrogen (middle panel) and phosphorus (bottom panel) at the Upstream site of the Vaal River, South Africa.

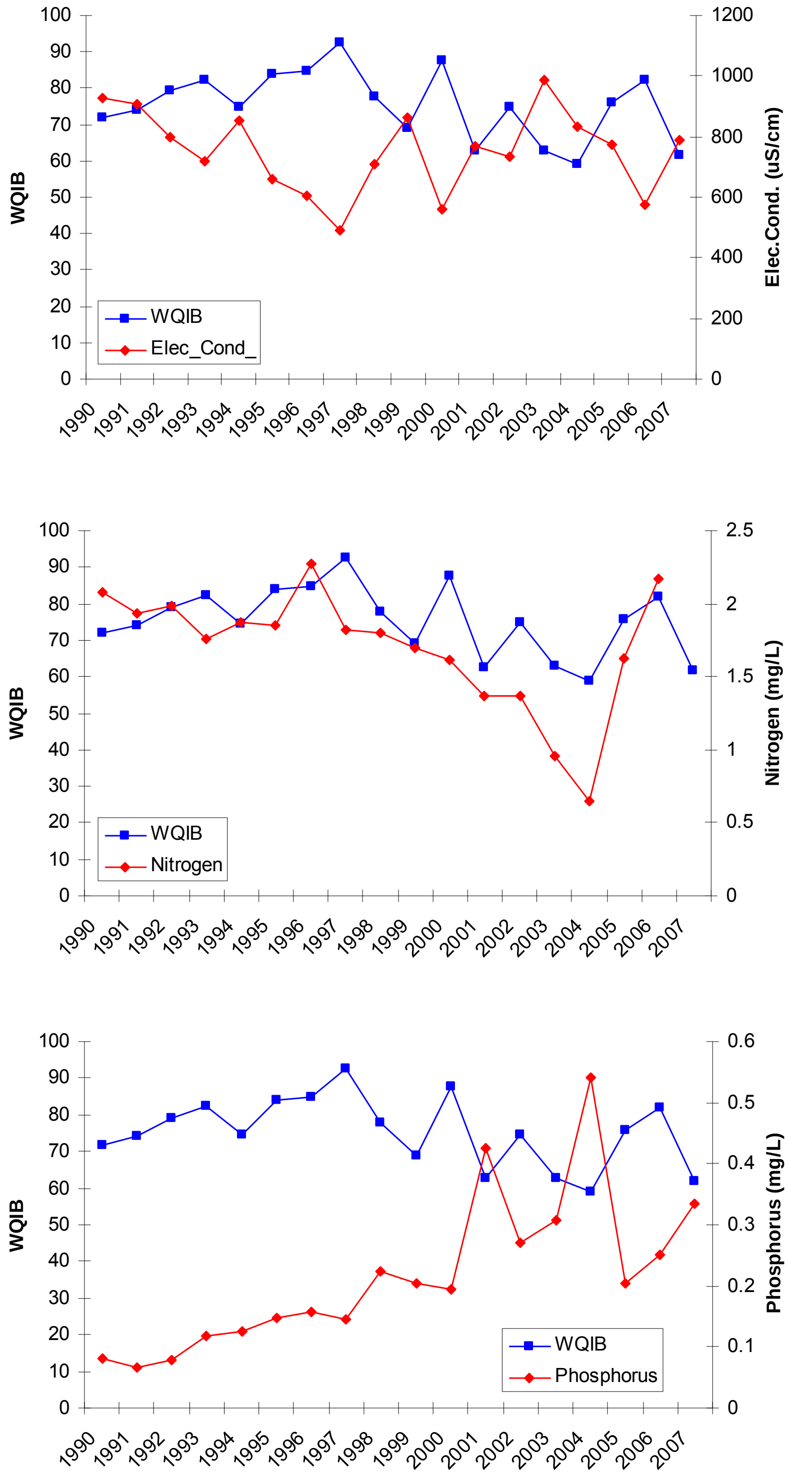


Figure 8 Water quality index for biodiversity (WQIB) scores and mean annual concentrations of electrical conductivity (top panel), nitrogen (middle panel) and phosphorus (bottom panel) at the Mid to Upstream site of the Vaal River, South Africa.

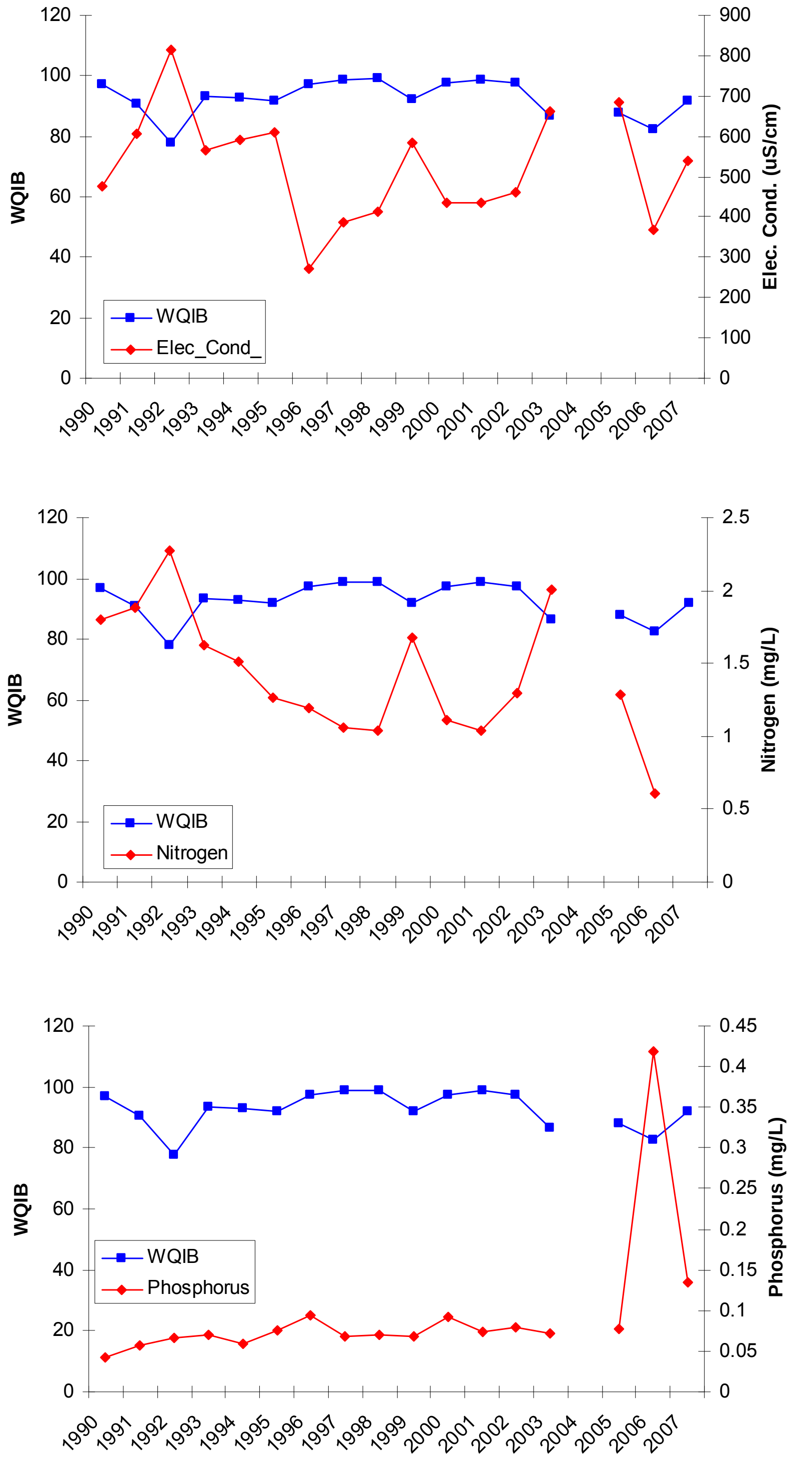


Figure 9 Water quality index for biodiversity (WQIB) scores and mean annual concentrations of electrical conductivity (top panel), nitrogen (middle panel) and phosphorus (bottom panel) at the Midstream site of the Vaal River, South Africa.

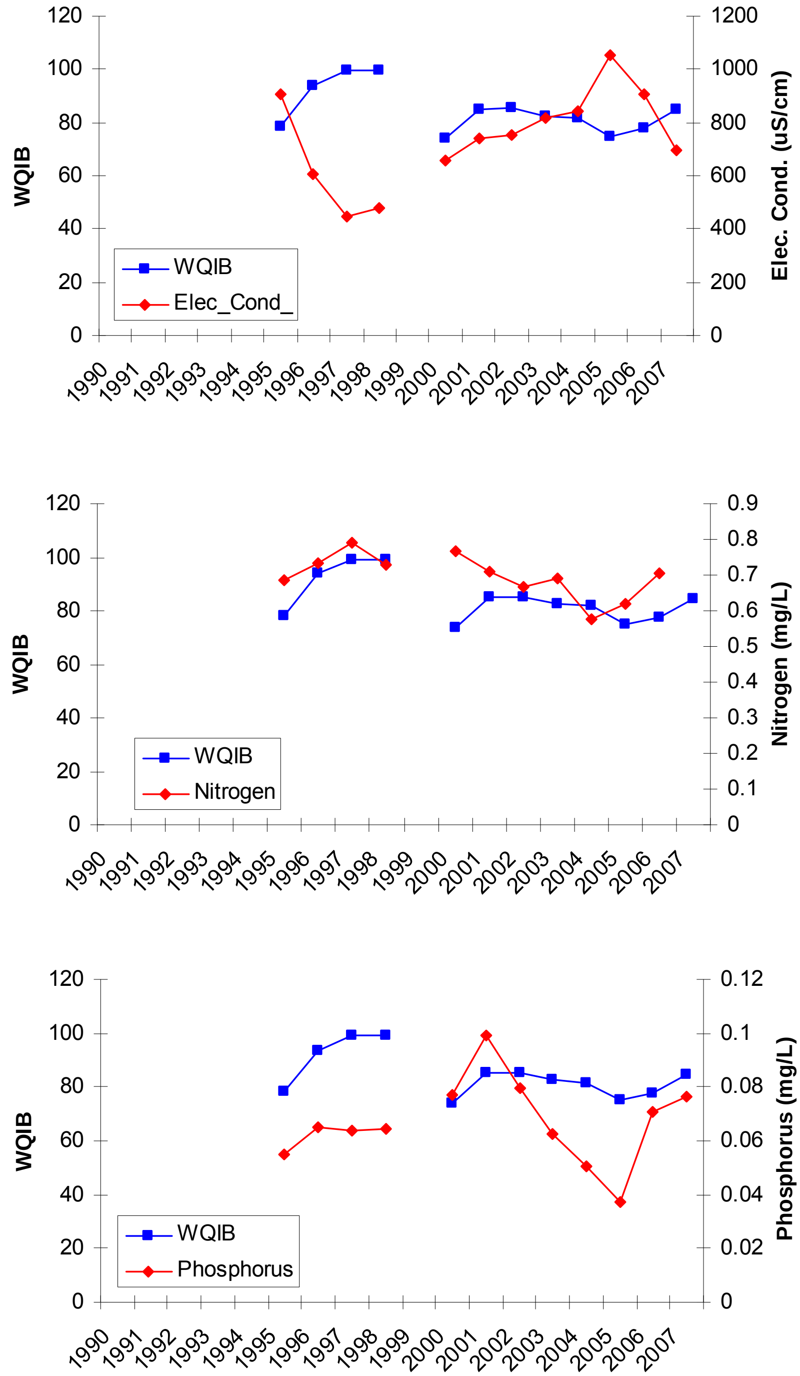


Figure 10 Water quality index for biodiversity (WQIB) scores and mean annual concentrations of electrical conductivity (top panel), nitrogen (middle panel) and phosphorus (bottom panel) at the Downstream site of the Vaal River, South Africa.

As conductivity and phosphorus seemed to play a predominant role in the WQIB, the concentrations of these parameters were plotted by site along with the guideline (Figure 11. At all four stations, phosphorus was consistently in exceedance, with the highest levels observed at the mid to upstream site. When we compare conductivity between sites, the two dam stations (Upstream and Midstream) have the lowest conductivity values, whereas the Mid to Upstream and Downstream sites are consistently high. Therefore, we can conclude that conductivity is driving the lower WQIB scores at the Downstream site and phosphorus and conductivity are driving the WQIB at the Mid-Upstream site.

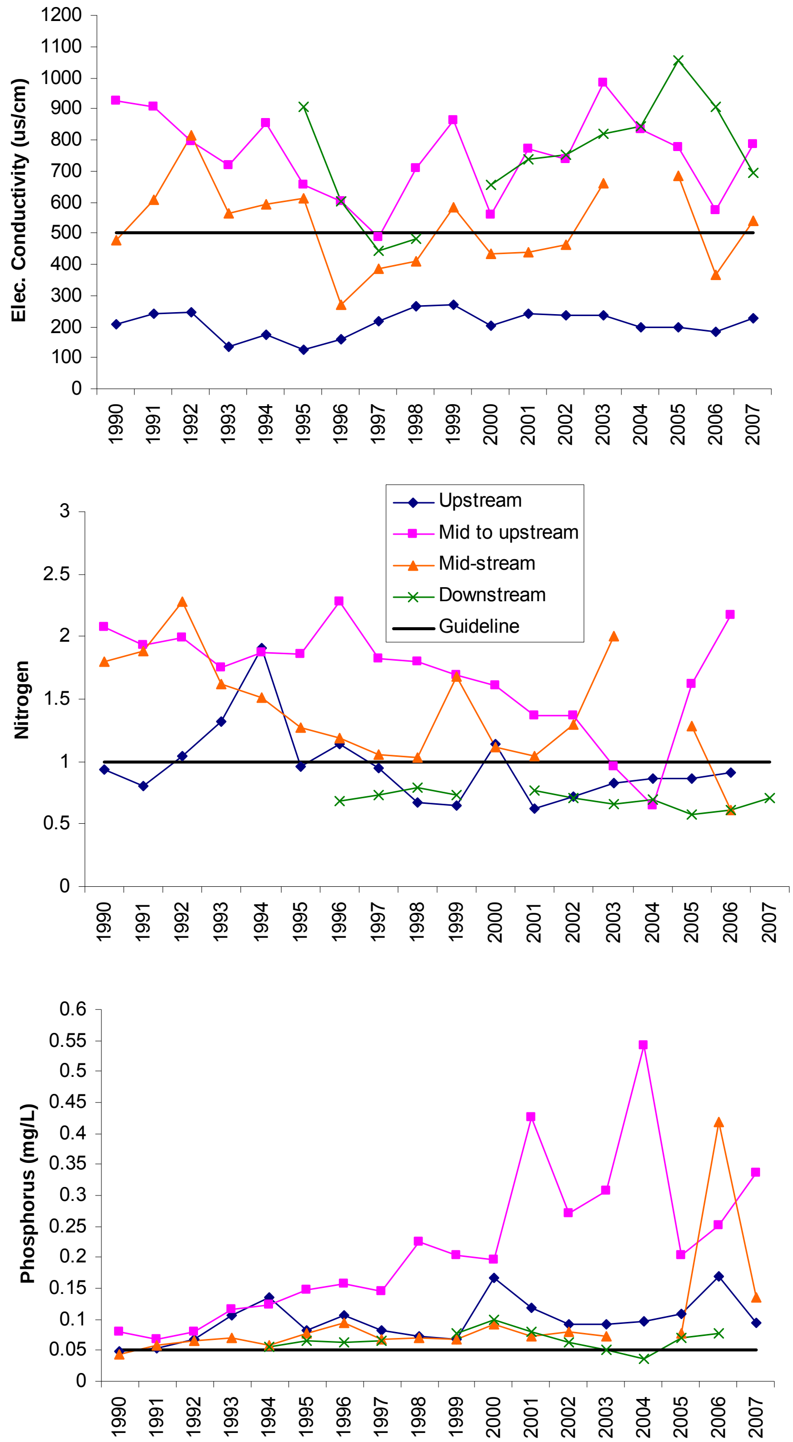


Figure 11. Relationship between mean annual phosphorus (top panel), electrical conductivity (middle panel) and nitrogen (bottom panel) and their target concentrations at four stations in the Vaal River, South Africa.

Flow/dilution effect

An investigation into the influence of water quantity on the concentration of the exceeding parameters was conducted. Flow rates were determined for two sites within the Vaal River (Mid to Upstream and Downstream sites) between 1995 and 2007 (Figure 12). There were three major peaks in annual flow rates at both stations in the Vaal River during the study period; 1996-97, 2000 and 2006. To assess the influence of flow on the WQIB and the concentrations of these parameters, Pearson's correlation analysis was conducted (Table 9).

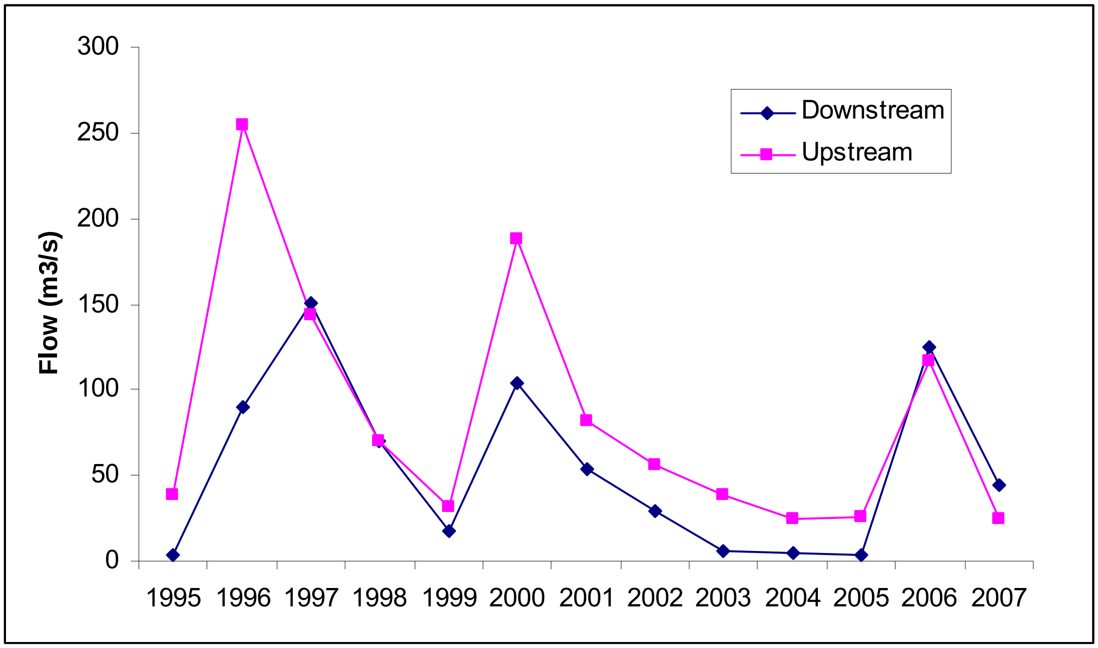


Figure 12 Flow rates (m^3/s) at the mid to upstream site (038004) and downstream site (038003) along the Vaal River, South Africa, between 1995 and 2007.

WQIB scores at the mid-upstream site were positively (though not significantly) correlated to instream flow (Table 9). The strongest and only significant relationship to flow at the mid-upstream sites was conductivity (r=-0.73, Table 9, Figure 13). In general, as flow increased, electrical conductivity decreased, explaining the positive (although not significant) relationship observed between flow and WQIB (r=0.56, Table 9). That is, electrical conductivity did not tend to exceed targets in years where water flow was high, and since conductivity is the variable most strongly correlated to WQIB scores (Table 8), this corresponded to higher WQIB scores in high-flow years. Interestingly, there was a weak positive relationship between nitrogen and flow, such that nitrogen tended to increase with increases in flow (r=0.307, Table 9; Figure 13).

Similar patterns were observed at the downstream site, with conductivity negatively and nitrogen positively correlated to flow (Figure 14; Table 9). WQIB scores were also weakly positively correlated to flow, probably as a result of the weak positive correlation between conductivity and flow. Nitrogen was the only parameter that was significantly correlated to flow, although both nitrogen and phosphorus were positively correlated to flow, and the strength of correlations of these nutrients was much stronger than at the mid-upstream site.

Table 9 Pearson's correlation coefficients comparing flow rates with WQIB scores and water quality monitoring data at two sites in the Vaal River, South Africa. Asterisks denote significance level of correlations, such that '*': $P \leq 0.05$ and '**': $P \leq 0.01$. Numbers in brackets denote sample size of correlations.

	Flow (m^3/cm)	
	Mid-upstream	Downstream
Electrical conductivity	-0.73 ** (18)	-0.63 (12)
Nitrogen	0.31 (17)	0.80* (11)
Phosphorus	-0.04 (18)	0.34 (12)
WQIB	0.56 (18)	0.40 (12)

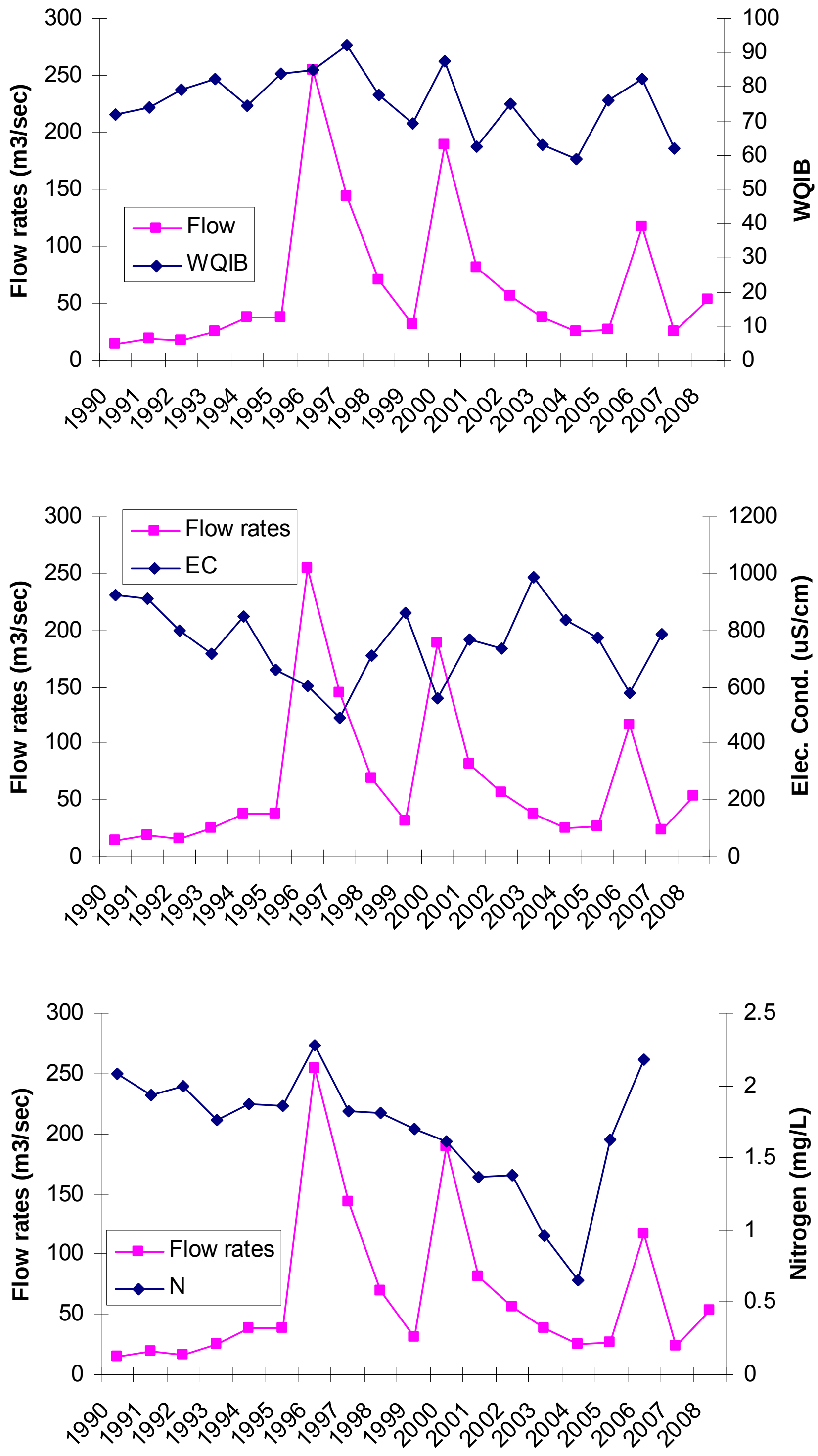


Figure 13 Flow rates (m^3/s) against WQIB, nitrogen and electrical conductivity at the mid-upstream site (038004) in the Vaal River, South Africa.

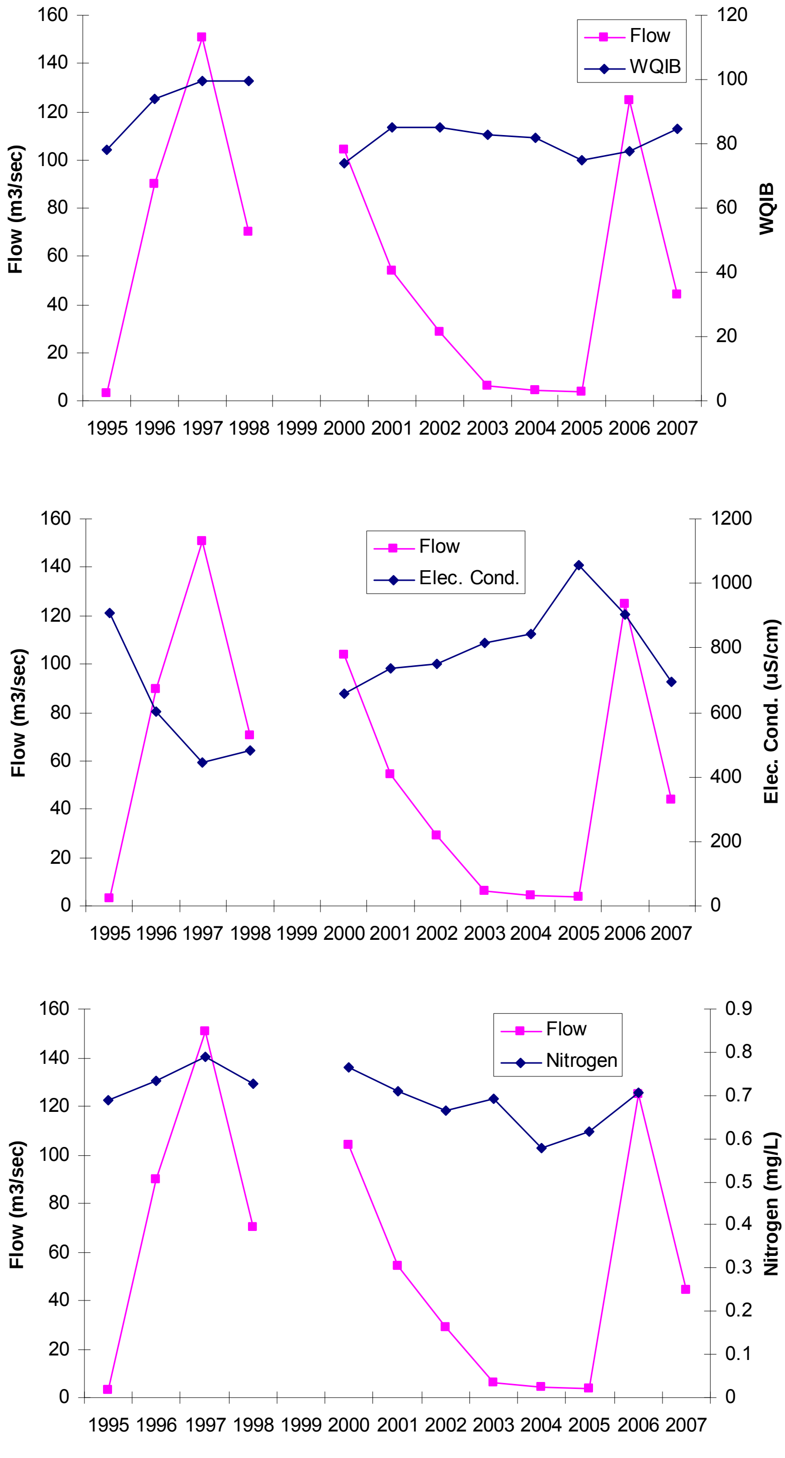


Figure 14 Flow rates (m^3/s) against WQIB, nitrogen and electrical conductivity at the Downstream (038003) site in the Vaal River, South Africa.

Discussion

The most consistent observation in this study was the effect of conductivity on the WQIB. An increase in conductivity led to a drop in the WQIB score that was particularly evident at the mid-upstream and downstream sites. A number of studies have looked at numerous water quality parameters, including conductivity, within the Vaal River. van Vuuren and Pieterse (2005) observed spatial differences in nutrient concentrations and salinity (a measure of conductivity) along the Vaal River. High nutrient concentrations and low conductivity levels were reported in the upstream section of the river, whereas decreases in nutrients and increases in salinity and conductivity were observed in the downstream area. Roos and Pieterse (1995) suggested that salinization and eutrophication were primarily responsible for declining water quality in the Vaal River system due to irrigation and dry-land farming. Braune and Rogers (1987) made a similar observation that the water quality in the Vaal River deteriorates as the concentration of dissolved salts increases downstream primarily due to inputs by mining, industrial and human effluents. Irrigation return-flow is also contributing to increased salinity in the Vaal River, particularly in the region below the Barrage (Braune and Rogers, 1987). These observations correspond with results from this study showing that the WQIB deteriorates from upstream to downstream and is particularly low at the highly impacted mid-upstream site south of Johannesburg.

Flow rates have been shown to have an effect on salinity, and therefore conductivity. Roos and Pieterse (1995) observed that the lowest salinity rates were recorded during flood periods within the Vaal River. Our flow data correspond with the observation that with increased flow, WQIB rises due to a drop in conductivity. Interestingly, nutrients were positively correlated with flow. This is possibly due to run-off from agricultural areas and/or urban discharges in the drainage basin of the Vaal River. To investigate the relationship between flow, run-off and nutrient increases, precipitation data for the mid-upstream area (where the highest concentrations were observed) were assessed. We observed a positive correlation between precipitation and both nitrogen ($r=0.65$) and phosphorus ($r=0.21$). Flow rate was not correlated with precipitation which was not surprising as flow is highly regulated in the Vaal River due to the Vaal and Bloemhoef Dams that are located in the upstream and mid-stream areas of the river. Our observations could suggest that increased precipitation leads to pulses of nutrients into the Vaal River due to run-off from agricultural areas in the mid-upstream sites. Increased flow rates (predominantly controlled from the dams) reduced conductivity and salinity issues downstream leading to an improvement in the WQIB. The influence of flow on water quality within the Vaal River should be assessed in more detail.

The increasing trend in nutrients (total phosphorus) may be a reflection of urban development at the mid-upstream site. A number of studies have determined that water quality in areas dominated by agricultural activity are characterized by high nitrate, nitrite and TSS (Ndiritu et al, 2006; Leland and Porter, 2000) whereas those in residential and industrial areas have increased levels of TDS, phosphate, conductivity, alkalinity and temperature (Lobo *et al.*, 1995; Juttner *et al.*, 2003; Ndiritu *et al.*, 2006). When we assess the spatial trend of water quality parameters in our study, the mid-upstream site is reflected by elevated nitrogen, phosphorus and conductivity whereas the downstream site is only reflected by elevated conductivity. Elevated nitrogen and phosphorus could be due to both agricultural and sewage effluents which would suggest that the WQIB is reflecting agricultural and urban impacts in the mid-upstream site. In comparison, elevated conductivity at the downstream site would suggest that the WQIB is reflecting mainly industrial influences in this area.

Water quality and biodiversity

Taylor *et al.* (2007) conducted a study in the Vaal River to assess diatom indices and their link to water quality variables. In their study, electrical conductivity was negatively correlated with a number of diatom indices, the strongest being the biological diatom index (r=-0.63) and specific pollution sensitivity index (r=-0.50). Given that the driving factor of the WQIB in the Vaal River was also conductivity, we would expect the WQIB to reflect changes in biological parameters such as the diatom indices studied by Taylor *et al.* (2007).

National Biomonitoring Programme for Aquatic Ecosystems (NBPAE, 2003) conducted biomonitoring along numerous rivers in South Africa, including the Vaal and Orange rivers. In terms of biological integrity, the overall health of the middle and lower Vaal River was rated fair to poor. Specifically, biodiversity indices rated sampling areas downstream of the upstream site, i.e., around the mid-upstream site in our study, as fair to poor. At the downstream site biotic indices were rated fair; these results compare well with our WQIB.

The NBPAE study also concluded that other than reduced flow in the Orange River, the available habitat upstream of the Gariep Dam is relatively unimpacted and the overall health of the area is good. In addition, downstream of the Vanderkloof Dam and towards Douglas (our mid-stream site on the Orange River) biotic indices were rated fair to good. Again, this corresponds well with our WQIB for the Orange River which rated all sites as good-excellent (Figure 6).

This validation analysis confirmed that 1) the WQIB was reflective of real data and 2) real data were accurately reflecting both anthropogenic influences and biodiversity measures in the Vaal River.

Chapter 5: Index Interpretation and Progress towards 2010 Target

As mentioned above, the international community has committed “to achieve a significant reduction of the current rate of biodiversity loss at the global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on earth by 2010”.

The WQIB can be used to track progress toward the 2010 Target in aquatic environments by quantifying the rate of change of water quality at monitoring stations. As water quality is directly correlated to biodiversity, a degradation of water quality can be expected to result in a loss of biodiversity.

At the most basic geographic unit, WQIB scores can be interpreted over time at individual monitoring stations and compared to raw water quality monitoring data to interpret patterns observed. There are many ways to extrapolate station by station patterns to larger geographic units, such as by drainage basin, freshwater ecoregion, country, continent or the globe. Patterns in the number of stations classified as poor to good or in average WQIB scores can be examined over time in the geographic unit of interest.

General declines in the percentage of stations classified as Good or Excellent were detectable in the Americas and Europe dating back to the 1970s and 1980s (Figure 15). Water quality in Asia and Oceania appears to have increased in the last decade or two, as the proportion of stations classified as Excellent or Good has increased. Patterns in Africa were more variable, but it appears as though water quality has been declining, with fewer river and lake monitoring stations being classified as Excellent or Good in recent years.

Coincident with the patterns in the classification of stations are trends in average WQIB scores in each continent over time (Figure 16). That is, WQIB scores have generally increased in Asia and Oceania and decreased in the Americas and Europe. Water quality in Africa has tended to vary between marginal and poor classifications, with a general trend toward a classification of ‘poor’. Differences in trends when all data were included and when only those stations that have been recently monitored (i.e., data since 2002), regularly monitored (minimum of 5 years of data), and monitored over a long time span (minimum 10 year time span between beginning and end of record) were relatively small when examined at the continental region (Figure 16).

Increasing declines in water quality over time imply movement away from the 2010 target of reducing losses of biodiversity. To this end, although water quality in Europe and the Americas has declined in recent decades, the rate of decline has slowed compared to that of the late 1960s and 1970s, suggesting that the rate of loss of biodiversity in aquatic environments has also slowed. However, in order for there to be *recovery* of biodiversity in aquatic environments there needs to be actual improvements in water quality and not just a slowing of rates of deterioration. There do seem to be some general improvements in Asia and Oceania in this regard.

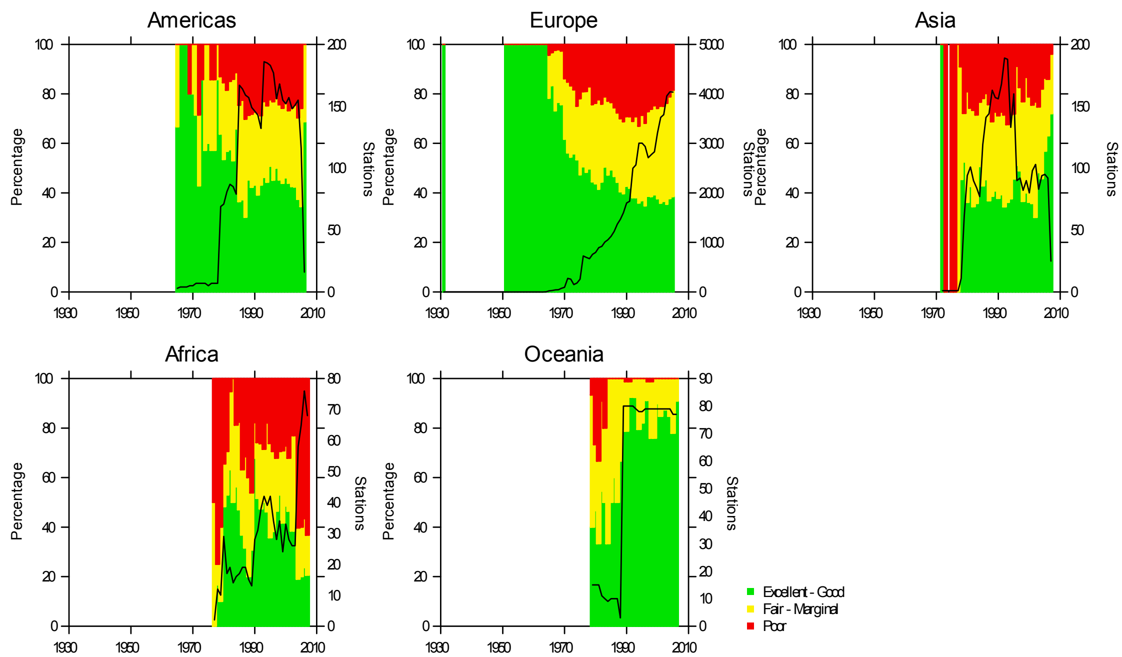


Figure 15. Percentage of excellent-good, fair-marginal and poor WQIB scores by geographic region and year. Black lines represent the number of stations reporting in each year.

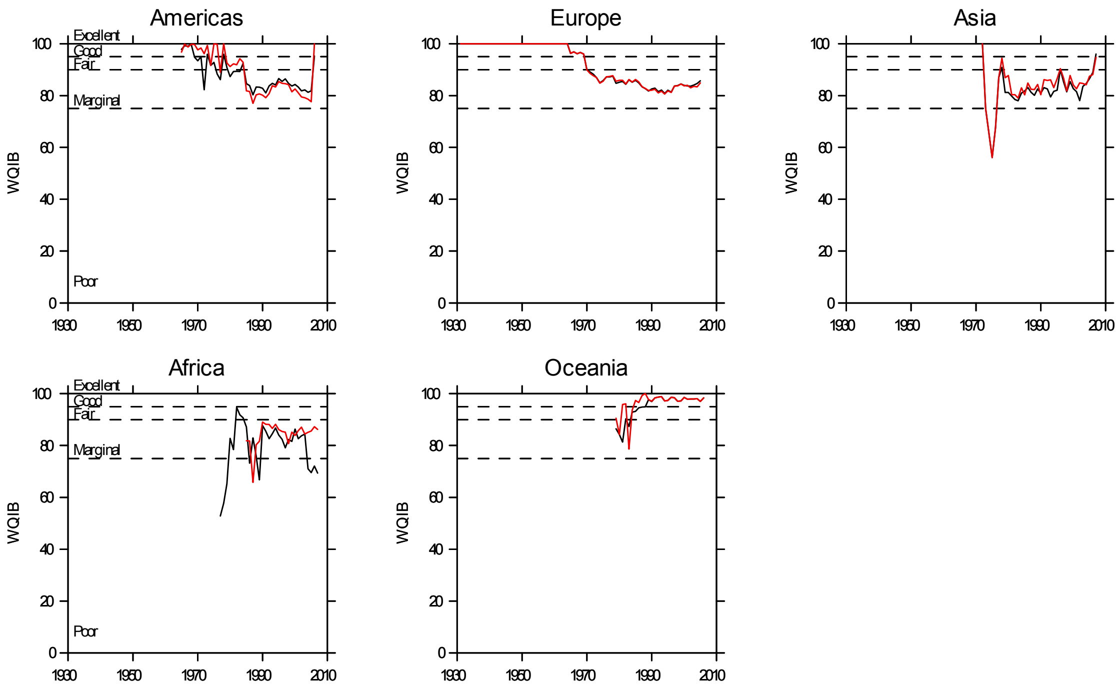


Figure 16. Mean water quality index for biodiversity (WQIB) scores by geographic region and year. Black lines are trends when all stations are included. Red lines are trends when only stations that have been monitored recently (since 2002), regularly (at least 5 years of monitoring data), and over a long time period (minimum of 10 year time span between beginning and end of monitoring record) are included. Dashed lines correspond to water quality classifications as shown in left hand panels.

To further quantify progress toward the 2010 target, recently monitored stations with long water quality time series were examined for station by station trends. Stations were considered to have been monitored recently if data were current to 2002 (the year of formal adoption of the 2010 target) or later. Stations were considered to have long water quality time series if they had at least five years of monitoring data spanning a minimum of ten years. These criteria reduced the data set from 6,216 to 3,387 monitoring stations (54% of stations). An additional 195 stations were not included in further analysis because there was no change in WQIB scores over the entire monitoring period. 76% of the records for which a WQIB was originally computed were included in this reduced data set. Linear regressions of the WQIB against monitoring year were conducted on a station by station basis. Model coefficients were examined to determine the direction of trends and the significance of trends (significance interpreted at $\alpha \leq 0.05$).

Water quality has improved, as measured by increases in WQIB scores (i.e., the slope of the WQIB – Year relationship was positive), at approximately twice the number of long-term water quality monitoring stations as where it has deteriorated (2,152 stations with increasing versus 1,040 with decreasing WQIB scores). Exactly half of the increasing trends detected were significant at the 95% confidence level, whereas only 36% of decreasing trends were significant.

The patterns are strongly driven by water quality changes in Europe, where WQIB scores increased at more than double the number of stations as where scores decreased (Figure 17). Water quality in Asia has improved at only slightly more than half the number of long-term monitoring stations, whereas it has declined more in the Americas. Declines were also noted in Africa. The number of stations increasing and decreasing in Oceania is approximately the same, indicating that, on average, water quality has not changed much in this region.

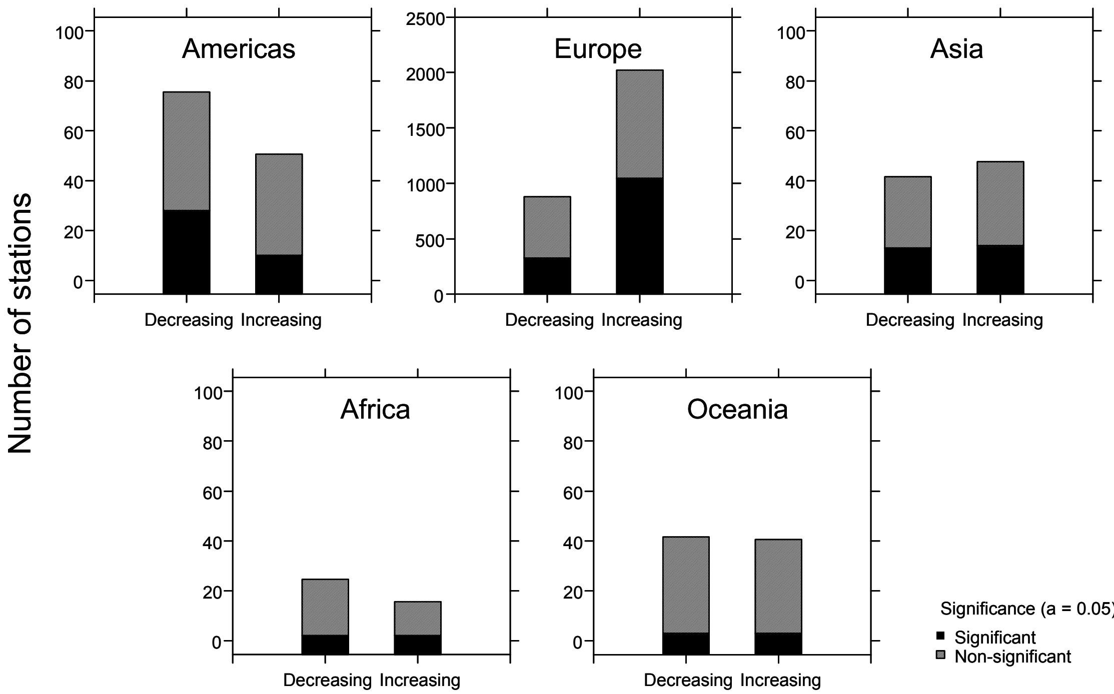


Figure 17. Number of stations with increasing and decreasing trends in water quality by region. Trends inferred by the direction of slope of station by station linear regressions of WQIB scores against monitoring year. Significance of trends inferred at $\alpha \leq 0.05$. Only recently monitored (last reporting year no earlier than 2002), long term (minimum 10 year time span from beginning to end of monitoring period) and active (minimum five years' of data within the time span) stations were included for trend analysis. Note difference in scale of y-axes.

Effect of number of stations

Somewhat confounding the interpretation of regional trends in water quality is the fact that the number of stations reporting in any given year can change dramatically, so that comparisons over time within a region are not necessarily reflective of actual trends in water quality at individual stations but more of the fact that fewer or more stations were reported. This change in station numbers was most evident in Europe, where over 4,000 stations reported water quality data in the mid-2000s, compared to fewer than 100 stations that reported in the 1980s (Figure 15).

When WQIB scores were examined and classified on a yearly basis, there is a strong negative correlation between average WQIB and number of stations (r = -0.94, P <0.0001) and between the proportion of stations classified as Excellent-Good and number of stations (r = -0.98, P < 0.0001). However, this relationship begins to break down when examined by ecoregion and year (Figure 18). Correlation coefficients between number of stations and proportion of stations in each classification were more than halved (-0.40 ≤ r ≤ 0.42); the correlation between WQIB and number of stations was also much lower (r = -0.32, P < 0.0001). The reduced strength of correlations is due to the fact that the pattern between index scores (or classification of scores) and number of stations is not consistent across geographic regions. Thus, a negative correlation between number of records classified as Excellent – Good and number of stations exists for Europe and the Americas, but the relationship is positive for Oceania, Asia and Africa (Figure 18).

Further breakdown of the data to freshwater ecoregion yields a total loss of correlation between the WQIB and number of stations within the entire data set; correlations are sometimes significant at the ecoregion scale but there is no consistency in the direction of trends. Thus, the effect of station number on WQIB trends is really only most important at large regional scales and disintegrates at finer scales.

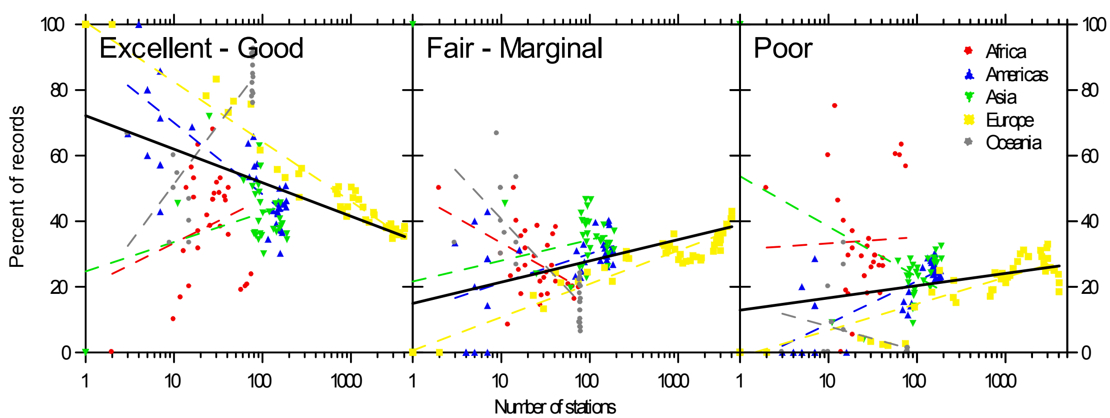


Figure 18 Relationship between the percent of records classified as Excellent-Good (left panel), Fair-Marginal (middle panel) and Poor (right panel) as a function of the number of stations. Data are divided according to geographic region (continent) and each point represents data for one year. The thick black lines are the linear correlations between percent of records and number of stations (r=-0.40, 0.42, 0.20 for left, middle and right panels) and are significant at P ≤ 0.02. Dashed lines are correlations on a regional basis and are not necessarily significant.

Assessment of WQIB by Freshwater Ecoregions of the World

The interpretation of water quality at a continental scale is necessarily very general, and it is obvious that both water quality and biodiversity in aquatic environments vary naturally over the scale of a continent. Freshwater ecoregions of the world have been delineated based on the distribution and composition of freshwater fish species and on major ecological and evolutionary patterns (Abell *et al.,* 2008). Because they are biogeographical units, the freshwater ecosystems of the world can be used to better reflect changes in regional water quality as it relates to biodiversity. To this end, water quality monitoring stations from which a WQIB was computed cover 183 out of a total of 426 freshwater ecoregions globally. The number of stations that fall within the different ecoregions varies greatly, from 1 to over 1,300 stations, while ecoregion area ranges from < 25 to > 4,500,000 km^2 and can encompass up to 16 countries (Abell *et al.,* 2008). Temporal coverage across ecoregions varies, with data from over 100 ecoregions that is current to within the last ten years and with one and 55 years of data from within any one ecoregion. The patterns in water quality from three reasonably well-represented (in terms of number of monitoring stations and years of data) freshwater ecoregions were examined to demonstrate how water quality can be interpreted at finer regional scales.

Upper Mississippi (United States of America)

Water quality in the Upper Mississippi freshwater ecoregion of the United States has deteriorated since the 1990s (Figure 19). The average WQIB score for the ecoregion has dropped since a peak in the mid-1990s, and none of the 5 to 8 stations that reported water quality data since 2002 could be classified as Excellent or Good. A study of a subset of four stations within this ecoregion showed that water quality was classified as Poor at all but one station and deteriorating conditions were evident at these three stations with among the lowest WQIB scores having been measured in the last five to seven years.

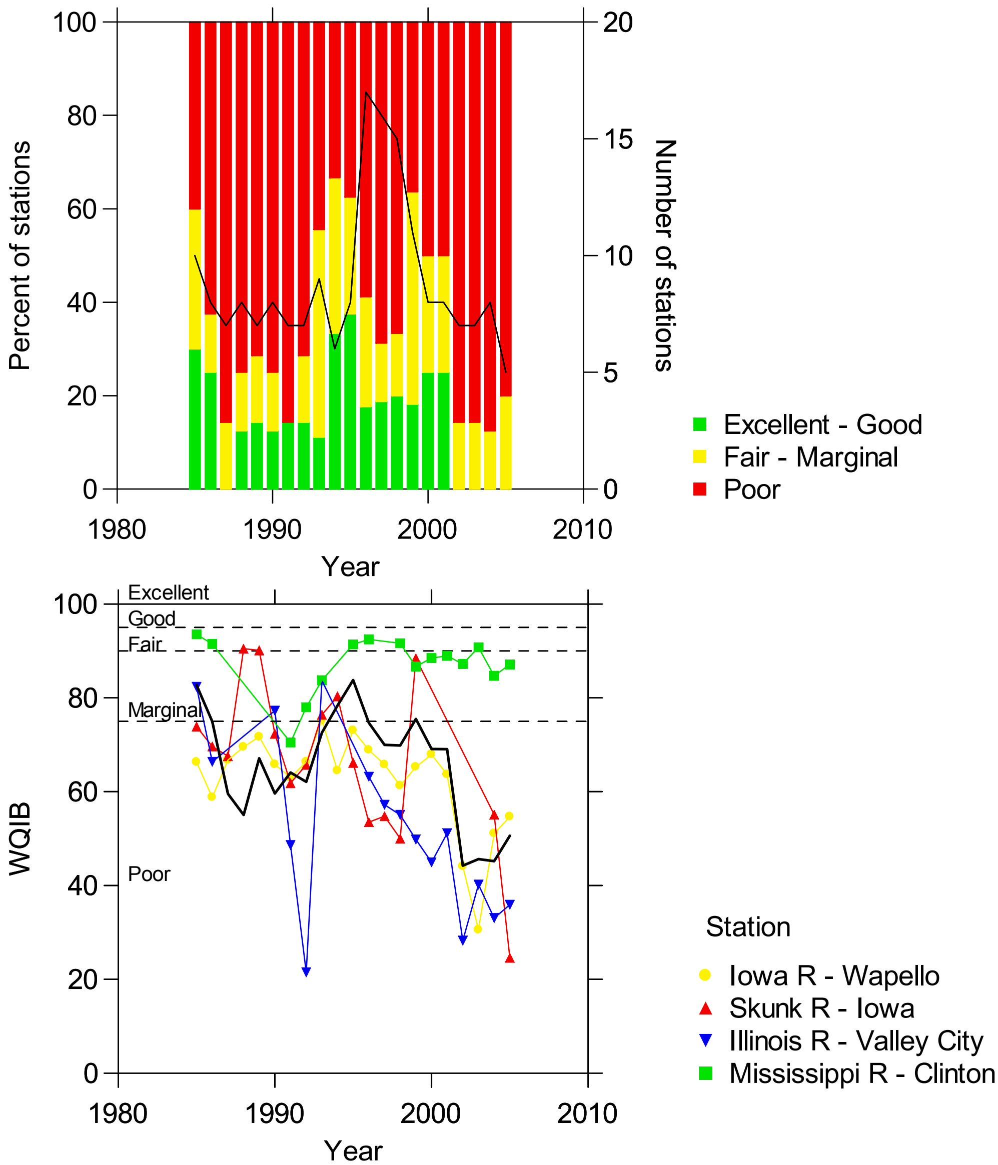


Figure 19 Trends in water quality index for biodiversity (WQIB) in the Upper Mississippi freshwater ecoregion of the United States. Top panel: Percentage of excellent-good, fair-marginal and poor WQIB scores by geographic region and year. Black line represents the number of stations reporting in each year. Bottom panel: Temporal trends in WQIB scores at four monitoring stations (coloured lines with symbols as in legend) and average scores for the entire ecoregion (thick black line). Dashed lines correspond to WQIB classifications as shown.

There were only 7 of a possible 19 stations for which long term trends could be evaluated in the Upper Mississippi freshwater ecoregion. Of these, 6 out of 7 showed decreasing WQIB scores and only 1 station saw a non-significant increase in WQIB scores (Table 10).

Table 10. Number of stations with increasing and decreasing trends in water quality in the Upper Mississippi freshwater ecoregion of the United States of America. Trends inferred by the direction of slope of station by station linear regressions of WQIB scores against monitoring year. Significance of trends

inferred at $\alpha \leq 0.05$. Only recently monitored (last reporting year no earlier than 2002), long term (minimum 10 year time span from beginning to end of monitoring period) and active (minimum 5 years' of data within the time span) stations were included for trend analysis.

Direction of trend	Number of stations	
	Significant	Non significant
Increasing	0	1
Decreasing	4	2

Cantabric Coast – Languedoc (France and Spain)

The patterns in water quality in the Cantabric Coast – Languedoc (France and Spain) freshwater ecoregion are different than those of the Upper Mississippi ecoregion. First, water quality appears to have improved in the region since the early 1980s as evidenced by an increase in the proportion of stations classed as excellent-good and by an increase in mean WQIB scores across the ecoregion (Figure 20). The number of stations reporting water quality has steadily increased over the same time period, meaning that only a few stations reported water quality for the entire time period. Nevertheless, among the few stations examined here, trends in WQIB are fairly consistent despite the different reporting time periods: river monitoring data from a French and Spanish river (Bordeaux and Valduno) showed increases in water quality. Other stations have deteriorated, such as the French Galan monitoring station. Data from the French Garonne River showed deteriorating water quality through the 1980s followed by a general improvement in the mid 1990s. However, data were not reported past the mid 1990s for this station.

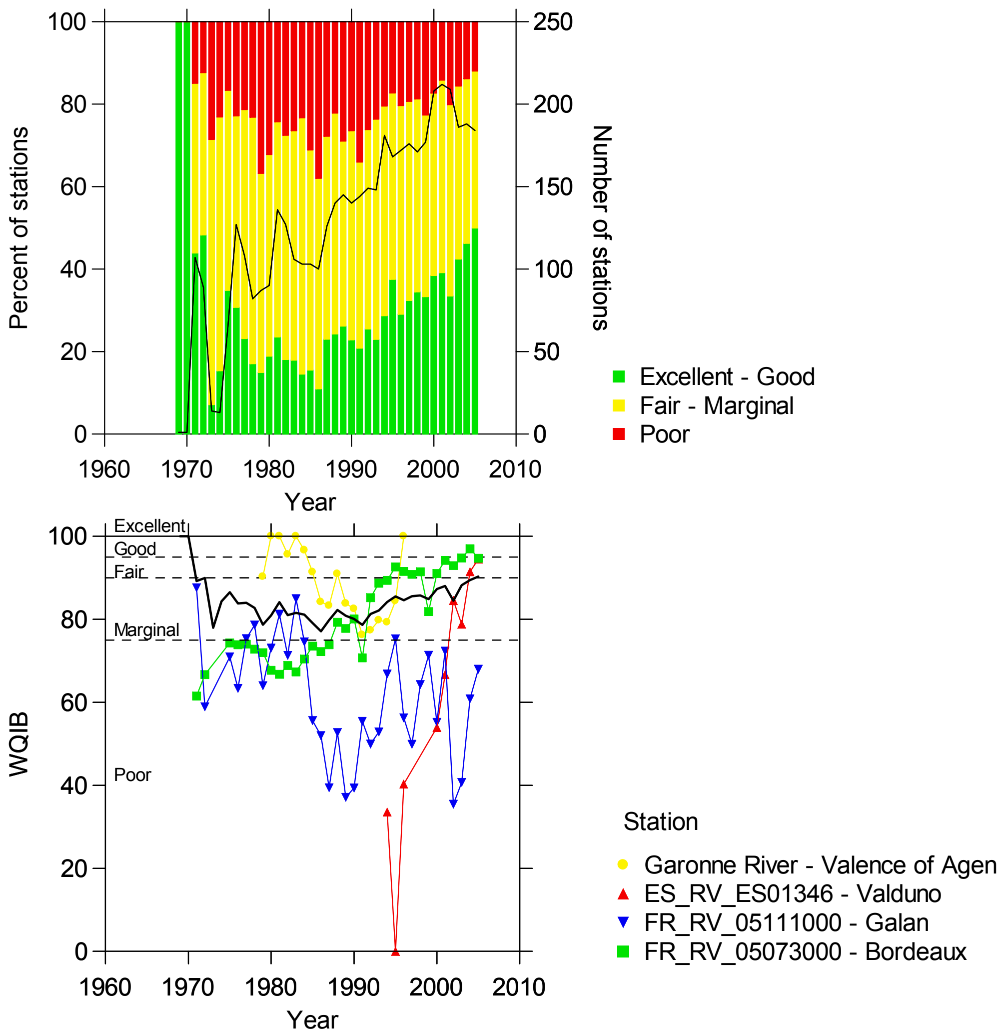


Figure 20 Trends in water quality index for biodiversity (WQIB) in the Cantabric Coast – Languedoc freshwater ecoregion of France and Spain. Top panel: Percentage of excellent-good, fair-marginal and poor WQIB scores by geographic region and year. Black line represents the number of stations reporting in each year. Bottom panel: Temporal trends in WQIB scores at four monitoring stations (coloured lines with symbols as in legend) and average scores for the entire ecoregion (thick black line). Dashed lines correspond to WQIB classifications as shown.

There were 185 out of 266 possible stations that could be evaluated for long term trends in WQIB scores in the Cantabric Coast – Languedoc freshwater ecoregion of France and Spain. Of these, 120 stations reported increasing WQIB scores, compared to 65 stations where scores declined over time (Table 11). The pattern in water quality at long-term monitoring stations mirrors that for overall WQIB scores in this ecoregion, in that water quality appears to have improved at more stations than it has deteriorated.

Table 11. Number of stations with increasing and decreasing trends in water quality in the Cantabric Coast – Languedoc (France and Spain) freshwater ecoregion. Trends inferred by the direction of slope of station by station linear regressions of WQIB scores against monitoring year. Significance of trends inferred at $\alpha \leq 0.05$. Only recently monitored (last reporting year no earlier than 2002), long term (minimum 10 year time

span from beginning to end of monitoring period) and active (minimum 5 years' of data within the time span) stations were included for trend analysis.

Direction of trend	Number of stations	
	Significant	Non significant
Increasing	53	67
Decreasing	10	55

New Zealand

Water quality in New Zealand (all one freshwater ecoregion) has consistently been excellent, with approximately 80% of stations having reported good-excellent water quality since the 1990s (Figure 21). This is also reflected in the mean WQIB scores and trends in a subset of stations from this ecoregion, where WQIB scores for most stations fall in the Good-Excellent or Fair-Marginal classification.

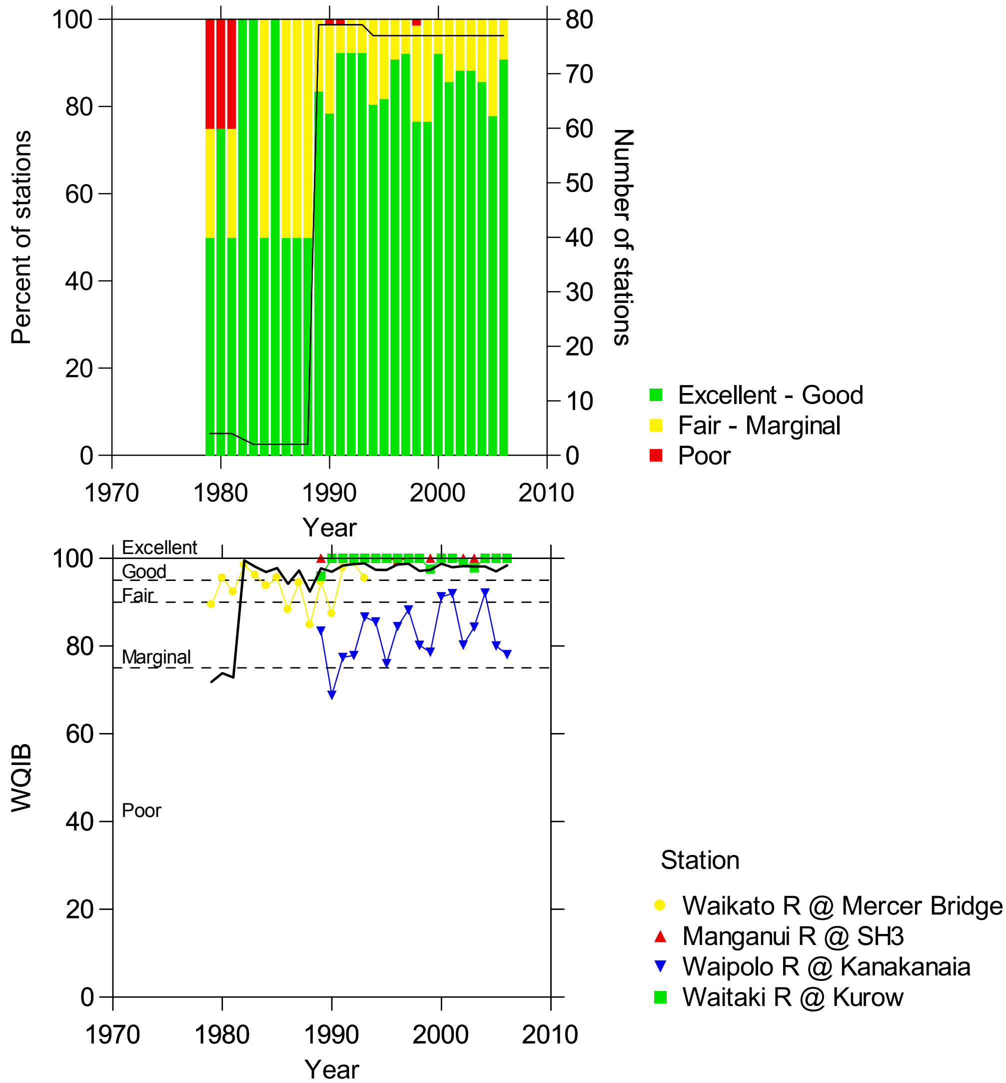


Figure 21 Trends in water quality index for biodiversity (WQIB) in the New Zealand freshwater ecoregion that covers the entire country. Top panel: Percentage of excellent-good, fair-marginal and poor WQIB scores by geographic region and year. Black line represents the number of stations reporting in each year. Bottom panel: Temporal trends in WQIB scores at four monitoring stations (coloured lines with symbols as in legend) and average scores for the entire ecoregion (thick black line). Dashed lines correspond to WQIB classifications as shown.

There were 77 out of a possible 81 stations that could be evaluated for long term trends in WQIB scores in New Zealand. Water quality has remained very stable in this freshwater ecoregion, with equal numbers of increasing and decreasing trends detected in WQIB scores over time. The majority of the trends were non-significant, indicating that any changes over time were too small to be detected statistically (Table 12). In fact, water quality did not vary by even one unit at eight of the long term monitoring stations.

Table 12. Number of stations with increasing and decreasing trends in water quality in New Zealand. Trends inferred by the direction of slope of station by station linear regressions of WQIB scores against

monitoring year. Significance of trends inferred at $\alpha \leq 0.05$. Only recently monitored (last reporting year no earlier than 2002), long term (minimum 10 year time span from beginning to end of monitoring period) and active (minimum 5 years' of data within the time span) stations were included for trend analysis.

Direction of trend	Number of stations	
	Significant	Non significant
Increasing	3	31
Decreasing	3	32
No change	0	8

Chapter 6: Summary and Future Development

The development of the Water Quality Index for Biodiversity is an important step in tracking progress toward meeting the 2010 Target of reducing loss of biodiversity in aquatic environments. Research has clearly shown a link between water quality and biodiversity; areas with declining WQIB scores can be expected to have declining biodiversity.

There are areas of the world that have shown considerable improvement in water resource quality. For example, clear improvements in water quality were detected in the Cantabric Coast – Languedoc freshwater ecoregion of France and Spain. Overall, there was approximately double the number of long-term monitoring stations in Europe with improving water quality as there were stations with declining water quality. Water quality in New Zealand has been and continues to be of very high quality. Water quality in some parts of South Africa also is consistently of good quality and deviations from good water quality are generally attributable to high conductivity readings. However, water quality continues to deteriorate in some parts of the world: WQIB scores have declined in the Upper Mississippi River basin of the United States, and more stations in the Americas have declining water quality than stations with improving water quality. Patterns in WQIB scores in Asia suggest recent improvements in water quality, with just over half of the long-term monitoring stations reporting increasing WQIB scores over time. Patterns in Africa are more difficult to interpret, primarily because of a lack of long-term monitoring stations, but trends suggest declining water quality on the whole.

The data used to develop the WQIB represent the most comprehensive data set for water quality in the world. However, there are large discrepancies in the global distribution of monitoring stations. Data collected and maintained by the UNEP GEMS/Water Programme originate from water quality monitoring authorities in individual countries as well as from collaborating focal points that are involved in water monitoring through research or other activities. Participation in the GEMS/Water Programme is voluntary. Reporting of water quality data to GEMS/Water is sometimes not regular, timely or from monitoring stations that are truly reflective of inland water quality within the country's boundaries. In contrast, European countries regularly report monitoring results to the European Environment Agency as part of the requirements of the Water Framework Directive. Reporting to the EEA is done at a much higher station density than for most of the rest of the world.

The WQIB proposed here will improve as more and more countries provide open and easy electronic access to water quality monitoring data. Participation in international programmes such as GEMS/Water can enhance global monitoring of aquatic resources and should be given priority status by national agencies. Such global programmes inform the world about wide scale patterns and may assist in the development of partnerships among regions experiencing similar environmental issues. However, the fact remains that capacity for monitoring in developing countries still needs to be developed and assistance from the international community in this regard would provide benefits that would extend beyond national boundaries.

Ideally, an index of water quality as it relates to biodiversity would include some measure of biodiversity in the ecosystem of interest. The index proposed here relies on chemical and physical water quality measurements to act as surrogates of biodiversity. The decision to use physical and chemical measurements as surrogates of water quality is justifiable since there are a number of published studies that demonstrate correlations between aquatic ecosystem diversity and water quality. However, the parameters chosen here do not, and can not, reflect all of the possible changes in water quality that may affect diversity. Thus, further validation of the index with actual diversity data would be highly valuable.

The need for comprehensive biological monitoring of aquatic ecosystems has been recognized at national and international levels. Countries such as the United States, Canada, Australia and member states of the European Union have all embraced different aspects of biological monitoring of aquatic ecosystems. Abundance and diversity of aquatic plants and algae, invertebrates, and fish and waterfowl are currently monitored in many inland waters around the world. However, at present there is no global database of biological monitoring data from which large patterns can be extrapolated. The UNEP GEMS/Water Programme recognizes the need for setting up such a database but has yet to find the resources to do so.

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