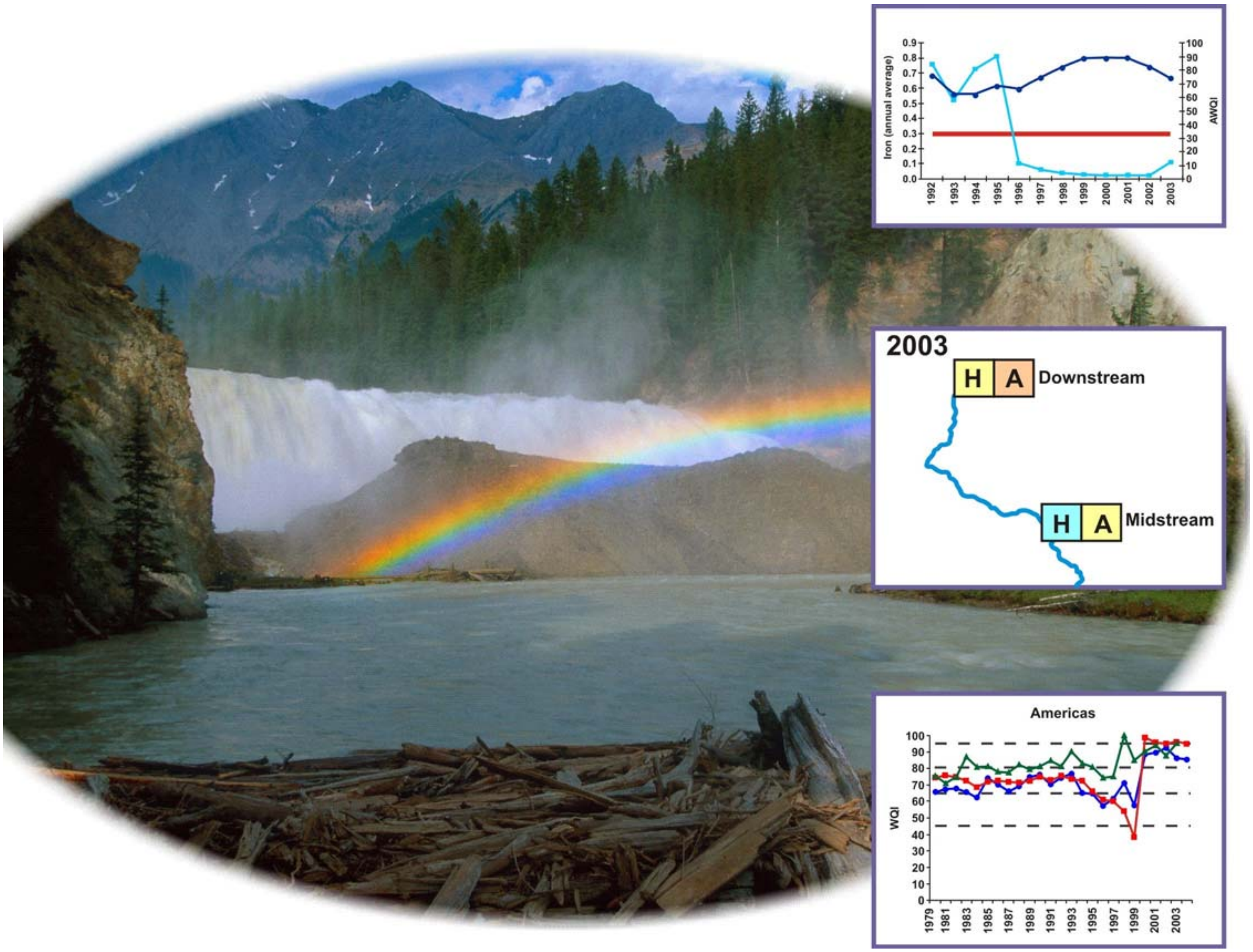

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GEMS Water

Global Drinking Water Quality Index Development and Sensitivity Analysis Report

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Chapter 1 Introduction

As the principal United Nations body on environment, the UN Environment Programme (UNEP) had been tasked by UN-Water to lead on freshwater quality and aquatic ecosystem data and information inputs to the World Water Assessment Programme, and the main WWAP output, the *World Water Development Report* series. Part of this task involves developing global water quality indicators and ultimately, a global water quality index.

UNEP delegated this responsibility to its GEMS/Water Programme, with direction to convene an international experts' workshop designed to implement the indicators and index requirements.

The workshop, attended by a group of selected indicator specialists, was convened at IAEA headquarters in Vienna, Austria (May 4th – 6th 2005) with the objective of reviewing the topic of water quality indicators/indices and making recommendations and suggestions on approaches and actions that GEMS/Water might consider in its future operations. The experts' first recommendation was that GEMS/Water should develop a pilot study to develop an index to assess the global status of drinking water in source water supplies (UNEP GEMS/Water, 2005). The experts' recommendation report is available on the GEMS/Water website.

This report presents the results of implementing the experts' first recommendation. It outlines an approach taken to develop a global water quality index, as well as preliminary sensitivity analysis and validation of the index against real water quality data. Limitations to the index are discussed, as well as next steps.

Composite Indices of Water Quality – a Review

Any number of water quality measurements can serve, and have already been used, as indicators of water quality. 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, a composite index that quantifies the extent to which a number of water quality measures deviate from normal, expected or 'ideal' concentrations may be more appropriate for summarizing water quality conditions across a range of inland water types and over time.

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). Summaries of the indices are given in Table 1, a full review of each index follows.

Pesce and Wunderlin (2000) compared the performance of three water quality indices on the Suquía River in Argentina. All three indices were calculated using observations for 20 different parameters that were normalized to a common scale according to observed concentrations and expected ranges. The 'objective' and 'subjective' indices were then calculated as a function of the normalized values, the relative weight assigned to each parameter, and, in the case of the subjective index, a constant that represented the visual impression of the contamination level of a monitoring station.

A third index, the 'minimal' index, was calculated as the average of the normalized values for only three parameters (dissolved oxygen, conductivity, and turbidity). The study reported that the minimal index was well correlated to the objective index, and that both water quality indices were generally correlated to the measured concentrations of different parameters.

In a study similar to the Argentinean one, Stambuk-Giljanovik (2003) compared the performance of several water quality indices for Croatian waters. All indices are similar to the objective index used in Argentina in that field measurements were normalized, or scored, on a parameter by parameter basis according to their observed concentrations and then a weighted average index was calculated from the normalized values. The indices were tested with data for nine water quality parameters collected monthly over one year at 50 sites in Croatia. Examination of the different water quality indices found that two modified arithmetic indices were best suited for discriminating sites according to water quality condition (good versus poor).

Liou *et al*. (2004) developed an index of river water quality in Taiwan that is a multiplicative aggregate function of standardized scores for temperature, pH, toxic substances, organics (dissolved oxygen, BOD, ammonia), particulate (suspended solids, turbidity), and microorganisms (faecal coliforms). The standardized scores for each water quality parameter are based on predetermined rating curves, such that a score of 100 indicates excellent water quality and a score of 0 indicates poor water quality. The index relies on the geometric means of the standardized scores.

Tsegaye *et al*. (2006) developed a chemical water quality index based on data from 18 streams in one lake basin in northern Alabama that summed the concentration of seven water quality parameters (total nitrogen, dissolved lead, dissolved oxygen, pH, and total, particulate and dissolved phosphorus) after standardizing each observation to the maximum concentration for each parameter.

Kim and Cardone (2005) developed a water quality index that evaluates changes in water quality over time and space. The Scatterscore index identifies increases or decreases in any water quality parameter over time and/or space. It does not rely on water quality standards or guidelines and can include an unlimited number of parameters. It was developed primarily to detect positive or negative changes in water quality around mining sites in the United States, but could be applied to non-impacted sites as well.

Sargaonkar and Deshpande (2003) developed the Overall Index of Pollution (OIP) for Indian rivers based on measurements and subsequent classification of pH, turbidity, dissolved oxygen, BOD, hardness, total dissolved solids, total coliforms, arsenic, and fluoride. Each water quality observation was scored as Excellent, Acceptable, Slightly Polluted, Polluted, and Heavily Polluted, according to Indian standards and/or other accepted guidelines and standards such as World Health Organization and European Community Standards. Once categorized, each observation was assigned a pollution index value and the OIP was calculated as the average of each index value.

The Well-being Assessment (Prescott-Allen, 2001) calculates a number of indices to assess global human and environmental condition. The indices were developed under two main categories:

1) Human well-being, including indices for health and population, which assesses both health life expectancy and total fertility rate, and, indices for wealth which assesses average household and national wealth; and

2) Ecosystem well-being, which includes assessment of both air, such as greenhouse gases and ozone depleting substances and water, such as inland water quality, river conversion and water withdrawal.

To establish an overall Well-being Index, the human and ecosystem indices are combined. The method yields a score for each country, with the top scores translating into a high quality of life for a low environmental price and the lower scores translating into a low quality of life for a high environmental price.

The Environmental Performance Index (Esty *et al.*, 2006) is composed of 16 indicators that represent various policy-relevant objectives on a global scale. There are six policy categories: environmental health, air quality, water resources, biodiversity and habitat, productive natural resources and sustainable energy. These six categories are placed into two broad objectives: Environmental Health and Ecosystem Vitality which are then combined to give the overall Environmental Performance Index (EPI). To calculate the EPI, each of the 16 indicators are converted to a proximity-to-target measure and placed onto a 0 to 100 scale (100 is the target and zero is the worst observed value). Principle components analysis is then conducted with all the indicators to distinguish weights for each indicator and groupings into specific objectives and/or policy categories. Those without a clear designation on the PCA are placed into their policy categories after literature review and expert consultation. The EPI score is calculated on a country by country basis that results in a global ranking of countries.

Instead of normalizing observed values to subjective rating curves, the Canadian Water Quality Index (CWQI) compares observations to a benchmark, where the benchmark may be a water quality standard or site specific background concentration (CCME, 2001; Khan *et al*., 2003; Lumb *et al*., 2006). The CWQI quantifies for one station, over a predetermined period of time (typically one year), the number of parameters that exceed a benchmark, the number of records in a dataset that exceed a benchmark, and the magnitude of exceedance of the benchmark. The index is flexible in terms of the benchmarks that are used for calculation, and depends on the information required from the index: that is, guidelines for the protection of aquatic life may be used (when available) if the index is being calculated to quantify ecological health of the water, or drinking water quality guidelines may be used if the interest in the index is in drinking water safety. Alternatively, information describing natural background conditions for a station or region may be used as benchmarks when trying to quantify deviation from natural conditions. Sites at which water quality measurements never or rarely exceed the benchmark have high CWQI scores (near 100), whereas sites that routinely have measurements that exceed benchmarks have low CWQI scores (near 0).

Similar to indices of economic strength, such as Gross National Product (GNP), 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. 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.

Table 1: Summary of indices developed which 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 Well-being of Nations	Human and Ecosystem	Assesses human indices against ecosystem indices	Globally	Prescott-Allen (2001)
Environmental Performance Index	Environmental health and ecosystem vitality	Uses a proximity-to-target measure for sixteen indices categorized into six policy objectives	Globally	Levy *et al. (*2006)
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)

Model Selection

There are many global water quality issues, and a number of priority issues of concern. One of these is safeguarding human drinking water supplies. The protection of source water quality for domestic use (drinking water, abstraction etc) was identified by the experts' group as a priority for assessment. It was selected because of its significance to human health; could be conducted on a global scale; and the approach for assessment would be user-based and involve application of common guidelines such as those from the World Health Organisation (WHO) across multiple water quality monitoring stations.

The experts' group selected the CWQI as the model that UNEP GEMS/Water programme should follow in developing the global water quality index. This model was selected as it requires the use of a benchmark or guideline which allowed us to compare values to the World Health Organisation's Drinking Water Quality Guidelines (WHO, 2004; Table 2). The primary purpose of the WHO guidelines is to protect public health by describing guideline values for constituents of water or indicators of water quality. By applying the Canadian index model and WHO guidelines to our data set we were able to develop an index that uses globally accepted guidelines for drinking water.

The source for water quality data used to analyze and validate the index calculations is GEMStat, the online global database of water quality for inland waters maintained by GEMS/Water. GEMStat has over two million entries for lakes, reservoirs, rivers and groundwater systems, and its 2,800 monitoring stations include baseline, trend and flux stations (www.gemstat.org). GEMS/Water has recently broadened the scope of its datasets to cover parameters related to wastewater and sanitation, including metals, persistent organic pollutants, water-borne pathogens and micropollutants.

The development of a global index of water quality will not only allow assessment of changes in water quality over time and space but also evaluate successes and shortcomings of domestic policy and international treaties designed to protect aquatic resources. For example, a global index will be one tool for tracking progress toward meeting the Millennium Development Goals and the Plan of Implementation of the World Summit on Sustainable Development, as well as other internationally agreed goals and targets.

The approach developed and outlined in this report will be used as a framework for tailoring other types of global indices of water quality. The index described here will be used for source drinking water, but the data selection approach will be comparable for the development of other indices, such as biodiversity and eutrophication indices.

This report is broken down into a development stage (chapters 2 and 3), sensitivity analysis (chapter 4), followed by validation of the index against real data, outlined in a case-study using data from the Vistula River, Poland (chapter 5). Finally, future development of the indices for drinking water quality is discussed (chapter 6).

Chapter 2 Benchmark, Parameter, and Station Selection

The approach for developing an index for global source drinking water quality has three parts:

1) Selecting benchmarks (usually guidelines or standards) that are appropriate in assessing global water quality for human health;
2) Selecting parameters from GEMStat that have an appropriate benchmark and have reasonable global coverage; and
3) From this list, selecting only stations that measure parameters consistently on an annual basis.

Guideline Selection

World Health Organisation drinking water guidelines

Our first objective was to select water quality parameters that could be associated with an existing drinking water quality guideline. As the goal was to develop a global index, the parameters selected were based on those in the World Health Organisation's Drinking Water Guidelines (Table 2.). To assess the robustness of these guidelines, comparisons with drinking water quality guidelines currently in place in the European Union, Australia and USA were conducted (Table 3). For this comparison we selected some of the most common parameters measured and reported in our database (ammonia, pH, chloride, iron, lead, arsenic, copper and faecal coliform bacteria) and compared values (Table 3).

The guidelines for the parameters selected compared well across nations and international agencies, with little deviation from each other (Table 3). The only WHO guideline that was substantially higher than the others was ammonia (1.5 mg L^{-1}), when compared to the EU and Australian guideline of 0.5 mg L^{-1}. The ammonia guideline is set for aesthetic considerations rather than health (no health guideline exists for ammonia) due to its corrosive potential of copper pipes and fittings. The WHO guideline of 1.5 mg L^{-1} was set as an acceptability guideline based on taste and odour (specifically odour) and therefore was considered acceptable for the purposes of our index. It was concluded that based on the parameters selected, WHO drinking water quality guidelines were representative of a number of national guidelines currently in place, and, therefore were selected for use in our index development.

Table 2: List of WHO guidelines for chemicals held in GEMStat

Chemical	Unit	Guideline	Guideline remarks	Guideline type	Source
2,4 –D	mg L^{-1}	0.03	Applies to free acid	Health	Agriculture
Aldicarb	mg L^{-1}	0.01		Health	Agriculture
Aldrin and dieldrin	mg L^{-1}	0.00003		Health	Agriculture
Aluminium	mg L^{-1}	0.1	0.1-0.2-deposits	Acceptability	
Ammonia	mg L^{-1}	1.5	Odour	Acceptability	
Antimony	mg L^{-1}	0.02		Health	Treatment
Arsenic	mg L^{-1}	0.01	Provisional – health effects uncertain	Health	Natural
Atrazine	mg L^{-1}	0.002		Health	Agriculture
Barium	mg L^{-1}	0.7		Health	Natural
Benzene	mg L^{-1}	0.01		Health	Industrial Human
Boron	mg L^{-1}	0.5	Provisional – trtmt limits	Health	Natural
Cadmium	mg L^{-1}	0.003		Health	Industrial Human
Chloride	mg L^{-1}	250	200-300 –> tastes salty	Acceptability	
Chromium	mg L^{-1}	0.05	Provisional – health effects uncertain	Health	Natural
Copper	mg L^{-1}	2	Staining may occur below guideline	Health	Treatment
Cyanide	mg L^{-1}	0.07		Health	Industrial Human
DDT and metabolites	mg L^{-1}	0.001		Health	Pesticides for public health
Endrin	mg L^{-1}	0.0006		Health	Agriculture
Faecal coliform bacteria	counts/ 100mL	0		Health	
Fluoride	mg L^{-1}	1.5	Adjust for volume of water consumed	Health	Natural
Hardness	mg L^{-1}	200	500: taste threshold	Acceptability	
Hydrogen sulphide	mg L^{-1}	0.05	0.05-0.1 —> taste and odour threshold	Acceptability	
Iron	mg L^{-1}	0.3	Staining and taste	Acceptability	
Lead	mg L^{-1}	0.01		Health	Treatment
Lindane	mg L^{-1}	0.002		Health	Agriculture
Manganese	mg L^{-1}	0.4	Taste, odour, appearance may be affected at or below guideline (~0.1mg L^{-1})	Health	Natural
Mercury	mg L^{-1}	0.001	Total mercury (inorganic plus organic)	Health	Industrial Human
Nickel	mg L^{-1}	0.02	Provisional – health effects uncertain	Health	Treatment
Nitrate	mg L^{-1}	50	Short-term exposure	Health	Agriculture
Nitrite	mg L^{-1}	3	Short-term exposure Long-term exposure; Provisional – health	Health	Agriculture
pH		6.5	Minimum	Acceptability	
pH		8	Maximum	Acceptability	
Selenium	mg L^{-1}	0.01		Health	Natural

Chemical	Unit	Guideline	Guideline remarks	Guideline type	Source
Sodium	mg L^{-1}	200	Taste	Acceptability	
Sulphate	mg L^{-1}	250	250-1000; taste and odour, maybe laxative	Acceptability	
Total dissolved solids	mg L^{-1}	600	600 – 1000; taste	Acceptability	
Turbidity	NTU[1]	5	Appearance; 0.1 median for disinfection	Acceptability	
Zinc	mg L^{-1}	3	3-5 –> taste, films	Acceptability	

[1]*Nephelometric turbidity units.*

Table 3: Comparison of WHO drinking water guidelines for selected parameters against guidelines from the European Union (EU), United States (USEPA) and Australia

Parameter	WHO	EU†	USEPA	Australia
Ammonia	1.5 mg L^{-1}	0.50 mg L^{-1}	No GL	0.50 mg L^{-1}
pH	6.5-8	No G L^{-1}	6.5-8.5	6.5-8.5
Chloride	250 mg L^{-1}	250 mg L^{-1}	250 mg L^{-1}	250 mg L^{-1}
Iron	0.3 mg L^{-1}	0.2 mg L^{-1}	0.3 mg L^{-1}	0.3 mg L^{-1}
Lead	0.01 mg L^{-1}	0.01 mg L^{-1}	0.015 mg L^{-1}	0.01 mg L^{-1}
Arsenic	0.01 mg L^{-1}	0.01 mg L^{-1}	0.01 mg L^{-1}	0.007 mg L^{-1}
Copper	2.0 mg L^{-1}	2.0 mg L^{-1}	1.3 mg L^{-1}	2.0 mg L^{-1}
Faecal coliform bacteria	0 counts/100 mL	0 counts/100 mL	0 counts/100 mL	No GL

† *WHO guidelines for drinking water were used as a basis for the standards for the EU Drinking Water Directive.*

The WHO guidelines divide water quality parameters into two categories:

i. Health guidelines, which take into account chemical and radiological constituents that have the potential to directly adversely affect human health; and
ii. Acceptability guidelines, which include parameters that may not have any direct health effects but result in objectionable taste or odour in the water.

Water that is highly turbid, highly coloured or that has an objectionable taste or odour could lead the consumer to believe that the water is unsafe. Microbial guidelines are also outlined by the WHO, to prevent contamination, and/or ingestion of water that is contaminated with human or animal (including bird) faeces. As these microbial guidelines are regarded as a human health issue, they are classed, for our purposes, under the health guidelines.

When choosing the parameters to include in the index, we assessed microbial measurements because they are an important predictor of water quality and are commonly reported in GEMStat. However, the WHO guideline for faecal contamination is zero counts per 100 mL; that is, any detection within treated water intended for drinking is unacceptable. As the GEMS/Water monitoring stations, used in this index, can be classed as untreated water (i.e. source water), the current WHO guideline was considered too stringent.

Guidelines for microbes in source water have been suggested elsewhere. For example, the Government of Swaziland set guidelines for drinking water quality in rural areas which included a faecal and total coliform bacteria guideline at 10 counts per 100 mL for untreated water intended for drinking (Government of Swaziland, 1998). As microbial measurements were considered too important to omit from our index, a guideline of 10 counts per 100 mL was set for microbial parameters to account for the fact that GEMStat data are collected from untreated water as opposed to treated water intended for drinking.

Following the decision to use the WHO guidelines, a drinking water quality index was developed using both health (including microbial) and acceptability measurements. In addition, based on the health and acceptability categories defined by the WHO, two further indices were developed to allow assessment of water quality on two scales 1) human health issues and 2) human acceptability issues. Therefore, the three indices developed were:

1) Drinking Water Quality Index (DWQI); which includes all parameters from the WHO guideline including microbes; and
2) Health Water Quality Index (HWQI); in which only health and microbial measurements are included to assess human health issues; and
3) Acceptability Water Quality Index (AWQI); which only includes acceptability measurements.

From a purely human health perspective, the HWQI will provide a more relevant assessment of water quality as it includes only parameters that have the potential to result in adverse health effects in humans. The AWQI will provide assessment of the public's perception of the quality of water, rather than specific health issues, as it assesses parameters that may cause unacceptable taste or odour. These parameters do not necessarily have any detrimental health effects. The DWQI is composed of both the HWQI and AWQI and, as such, will give an overall 'big picture' as to the quality of water.

It is important to stress that while these indices should provide an overall picture of the quality of a body of water, they can not be relied upon to definitely determine if a water source is safe for drinking. Primarily because of a lack of available monitoring data, there are a number of parameters that were not included in the indices that could still adversely affect the safety or acceptability of water for drinking.

Non-detects and Zeros

The inclusion of non-detects and zeros into the indices were assessed due to the possibility of bias into the equation. Parameters that have a non-detectable value are due to concentrations in the water-body that are below the detection-limit (either method or instrumental). The detection limit (DL) for any of the parameters, can be either lower or higher than the respective guideline, that is, a specific method may have a detection limit of 5 mg L^{-1}, however the guideline is set at 2 mg L^{-1}. If the DL is greater than the guideline we are not able to assess whether the true value is in exceedance or not. This means that regardless of whether the parameter is detected it will always be in exceedance of the guideline. In contrast, if the detection limit is less than the guideline then we would be certain that the level measured was not in exceedance. The inclusion of non-detects where the DL greater than the guideline may produce false exceedances, whereas we know that if the DL less than the guideline it is a true non-exceedance value.

Due to this uncertainty when the DL greater than the guideline, all records with a value that was recorded as being 'below detection' and where the DL was greater than the guideline were removed. These are shown in Table 4. This does not mean that these parameters have been removed all together; only those observations that were reported as being non-detects and where the DL was greater than the guideline.

GEMStat contains some older records with reported values of zero that most likely represent measurements below analytical detection but where the detection limit is unknown. With the exception of faecal coliform bacteria (FCB), all zero values were removed from the database as they do not represent a true value and could produce false-negatives (i.e., non-exceedances), skewing the index in a favourable direction. In the case of FCB, zero is a true measure in that it implies that no FCB were detected in the sample.

Table 4: Parameters that had analytical methods with detection limits greater than the WHO guideline

Guideline Type	Parameter	Detection Limits	Guideline	Units
HEALTH	Arsenic	0.013 - 0.8	0.01	mg L^{-1} As
	Cadmium	0.0038 - 5	0.003	mg L^{-1} Cd
	Chromium	0.07-2	0.05	mg L^{-1} Cr
	Copper	5	2	mg L^{-1} Cu
	Lead	0.011 - 1	0.01	mg L^{-1} Pb
	Manganese	1 - 1.1	0.4	mg L^{-1} Mn
	Mercury	2 - 200	1	µg L^{-1} Hg
ACCEPTABILITY	Aluminum	0.102 - 1	0.1	mg L^{-1} Al
	Iron	0.5 - 1.2	0.3	mg L^{-1} Fe
MICROBE	Faecal coliform bacteria	16 - 110000	10	No. 100 mL^{-1} MF

Note: Detection limits show the range for different analytical methods.

Global Coverage - Sampling Frequency

Further refinement of the test database was needed to ensure that the parameters included in the index were adequately represented globally. Minimum global and regional coverage for each parameter was chosen. We determined criteria for the percent coverage of countries within each region: Asia, Africa, Americas, Europe and Oceania.

We selected three criteria: 20%, 35% and 50% coverage limits for each region to be assessed. That is, each parameter must be measured in either 20%, 35% or 50% of countries within each region. The results of this analysis are reported in Table 5. These data were broken down by WHO criteria: Acceptability, Health and Microbes.

Table 5: Parameters measured in 20%, 35% and 50% of countries in all regions: Europe, Asia, Africa, Americas and Oceania. Parameters are divided according to their category

	Acceptability	Health	Microbes
20%	Ammonia Chloride Iron pH Sodium Sulphate Zinc	Arsenic Boron Cadmium Chromium Copper Fluoride Lead Manganese Mercury Nitrate Nitrite	Faecal coliform bacteria
35%	Ammonia Chloride Iron pH Sodium Sulphate Zinc	Copper Fluoride Lead Manganese Nitrate Nitrite	Faecal coliform bacteria
50%	Ammonia Chloride Iron pH Sodium	Copper Fluoride Manganese Nitrate	Faecal coliform bacteria

It is evident that microbe and acceptability parameters are quite consistent at all three levels. However, at 35% and 50% a number of parameters under the health criteria are lost. Under the 20% criteria, a wider selection of parameters is included and, as such, improves the relevance of the indices (specifically HWQI). For this reason, the 20% criterion was selected as a global distribution guideline for the development of the indices. Thus, each parameter included in the index had to be measured in at least 20% of countries in each of the major regions.

Once these parameters were selected, three databases were created: 1) Drinking Water, 2) Health and 3) Acceptability. Once the databases were created, further refinement within each database was required.

Measurement Consistency – the 'Four by Four' Rule

Following selection of water quality parameters based on water quality guideline availability, as well as based on global and regional coverage of the different water quality parameters, the three databases that were generated for index calculation were further refined to only include data from stations where monitoring of several parameters was consistent over time. It is recommended by the Canadian Council of Ministers for the Environment (CCME, 2001), that a water quality index should not be calculated for a station with any fewer than four parameters and four sampling visits per year. Data should be selected from stations that have measured a minimum of any four parameters per year, and, that each of these parameters is measured at least four times per year, hence, the 'Four by Four' (4x4) rule. This rule ensures that only stations that regularly monitor parameters are included. Of course, by including this rule we are limiting our analysis to only those monitoring stations that have adequate replication, resulting in elimination of stations that have, for example, only three monitoring phases per year. It is suggested for future development that this rule be assessed to provide some analysis of the number and location of stations eliminated when this rule is implemented and a comparison with alternative rules e.g. a 3 x 3 rule be conducted.

For the purposes of this investigation, the 4x4 rule was applied to each database (Drinking, Health and Acceptability). This led to three refined databases with parameters selected that had met all of the following criteria:

1) Measured >20% country coverage in each region: Asia, Africa, Europe, Oceania and Americas;
2) Measured at least four times per year at stations that had measured at least four parameters; and
3) Had detection limits less than guideline and zeros removed (except for FCB).

The index calculation was then run on each database resulting in three indices:

1) Drinking Water Quality Index (DWQI; all parameters regardless of WHO designation);
2) Health Water Quality Index (HWQI; health and microbial criteria only); and
3) Acceptability Water Quality Index (AWQI; acceptability criteria only).

The calculation of the indices is described in the following chapter.

Chapter 3 Derivation and Application of the Index

The index equation is based on the water quality index (WQI) endorsed by the Canadian Council of Ministers of the Environment (CCME, 2001). The index allows measurements of the frequency and extent to which parameters exceed their respective guidelines at each monitoring station. Therefore, the index reflects the quality of water for both health and acceptability, as set by the World Health Organisation. The index is determined on an annual basis resulting in an overall rating for each station per year. This will allow both spatial and temporal assessment of global water quality to be undertaken.

Canadian Water Quality Index (CWQI) Equation

The CWQI equation is calculated using three factors as follows:

$$\text{WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right)$$

F_1 represents Scope: The percentage of parameters that exceed the guideline

$$F_1 = \left(\frac{\text{\# failed parameters}}{\text{Total \# of parameters}} \right) \times 100$$

F_2 represents Frequency: The percentage of individual tests within each parameter that exceeded the guideline

$$F_2 = \left(\frac{\text{\# failed tests}}{\text{Total \# of tests}} \right) \times 100$$

F_3 represents Amplitude: The extent (excursion) to which the failed test exceeds the guideline. This is calculated in three stages. First, the excursion is calculated

$$\text{excursion} = \left(\frac{\text{failed test value}}{\text{guideline value}} \right) - 1$$

NB: in the case of pH where a minimum and maximum guideline is given, the excursion equation must be run as above as well as in reverse i.e. guideline value/failed test value.

Second, the normalized sum of excursions (nse) is calculated as follows:

$$\text{nse} = \left(\frac{\sum \text{excursion}}{\text{total \# of tests}} \right)$$

F_3 is then calculated using a formula that scales the nse to range between 1 and 100:

$$F_3 = \left(\frac{nse}{0.01\text{nse} + 0.01} \right)$$

WQI Designations

The index equation generates a number between 1 and 100, with 1 being the poorest and 100 indicating the best water quality. Within this range, designations have been set by CCME (2005) to classify water quality as poor, marginal, fair, good or excellent. These same designations were adopted for the indices developed here. The designations are presented in Table 6.

Table 6: WQI Designations

Designation	Index value	Description
Excellent	95-100	All measurements are within objectives virtually all of the time
Good	80-94	Conditions rarely depart from natural or desirable levels
Fair	65-79	Conditions sometimes depart from natural or desirable levels
Marginal	45-64	Conditions often depart from natural or desirable levels
Poor	0-44	Conditions usually depart from natural or desirable levels

In addition to these designations, we have proposed applying treatment levels to each category, that is, the level of treatment required to obtain an adequate level of water quality for human consumption. Without expert opinion and validation the application of treatment levels to the designations is merely subjective and therefore, only included for the purposes of this report in reflecting the potential use of the indices. Validation and expert opinion should be determined before designations are applied, but we would propose applying treatment descriptions to each designation in future development of the index. For example, applying descriptions as to the level of:

1. Removal processes – pre-treatment, flocculation, sedimentation, coagulation and filtration; and
2. Inactivation processes – primary or secondary disinfection.

Assigning this type of description to the current designations would be a useful tool for attempting to assess the suitability of the water body under assessment.

Global Water Quality Index

The development of the three indices outlined in this report allowed assessment of water quality not only temporally on a station-by-station basis but also spatially across different regions, countries and/or watersheds. GEMS/Water is in a unique position to produce indices of this nature as it is the only UN body dedicated exclusively to global environmental water quality data and assessment. In addition to global assessments, the development of the indices also allows assessment of the GEMStat database in terms of suitability, strengths and limitations of the parameters, as well as highlighting the gaps in data that need to be filled or developed further. The use of the indices also allows for assessment of the suitability of the WHO guidelines, specifically, whether they are too stringent, or, whether additional parameters need to be included that are not assessed by the WHO.

With this in mind, the following sections focus not only on providing both a regional and watershed assessment of drinking water quality, but also on investigating parameter and/or guideline sensitivity for the purposes of improving the database and/or index calculation.

Once all three indices were calculated, they were plotted on a region-by-region basis over time (Figure 1). The index values were calculated as an average per region per year.

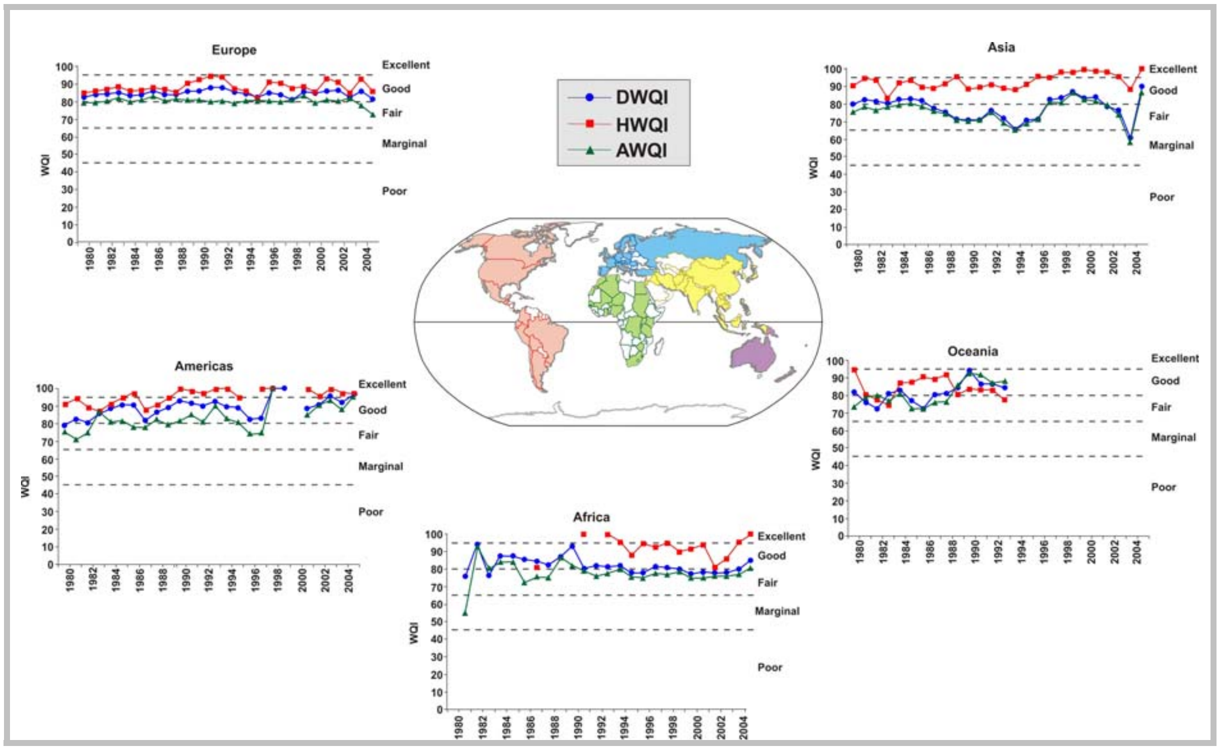

Figure 1: Temporal trends in water quality (DWQI, SWQI and AWQI) for the five regions (Africa, Americas, Asia, Europe and Oceania). Data represent annual averages for each region.

Within Europe, the indices show a similar pattern over time, with little deviation from the fair designation. Interestingly, HWQI is consistently lower than AWQI with DWQI falling between the two between the years 1978 to 1994. This would indicate two things. First, the acceptability of water, in terms of clarity, taste or odour, is much better than the quality of water with regards to human health aspects. Second, that DWQI is on the whole an average of the two indices. After 1994, there were improvements in HWQI which drove DWQI upwards, while AWQI stayed the same. It would seem that the water quality in Europe, with regards to acceptability, has been stable with no improvements or decreases over the last 30 years.

The pattern of water quality in the Americas and Africa was a little more erratic. In the Americas, DWQI followed HWQI consistently and, apparently, was influenced heavily by health parameters. Similar to Europe, AWQI was higher than the other two indices indicating again that the acceptability of water was much better than the quality of water with regards to human health. Specifically in the year 2000, both the Americas and Africa's HWQI dropped to the poor designation indicating a severe deterioration in water quality in both regions. However, this was short-lived as it was closely followed by a recovery to previous or better than previous levels in 2001. Further investigation into the drivers behind this drop is required to understand whether this is real, that is, reflective of the real data, or simply, a reflection of reporting errors or changes in the reporting rate of the parameters of interest in countries in both regions during that one year.

In Asia and Oceania, the water quality with respect to human health (HWQI) was consistently lower than AWQI (and DWQI in Oceania). In Asia, the DWQI closely followed HWQI regardless of AWQI, similar to the pattern observed in the Americas suggesting that DWQI is strongly influenced by health parameters rather than acceptability parameters.

Following this regional application of the index further analysis of the indices was performed. Firstly, analysis was conducted on each index to determine what, within the equation, was driving the index value. Was it the number of parameters exceeding guidelines, or the magnitude by which they exceeded? Secondly, analysis of the parameters contributing to the index was assessed by determining how many times (reported as a percentage of total exceedances) the parameter exceeded the guideline, and, how well they correlated with the final index value. By assessing the parameters individually we have some indication as to their influence over the final index. In addition, we are also able to assess the suitability of the guideline. If a parameter was consistently in exceedance then maybe the guideline is too stringent. Finally, once these assessments were conducted, a sensitivity analysis was performed to assess each parameters contribution to the final index value for both HWQI and AWQI. These analyses are reported in Chapter 4.

Chapter 4 Validation and Sensitivity Analysis

1) F_1, F_2 and F_3 Analysis

The index equation includes assessment of both extent and magnitude of excursions from the guidelines set by the WHO. By conducting sensitivity analyses we can assess whether the index is driven by how much each parameter exceeds the guideline (F_3), how many times it exceeds the guideline (F_2) or how many parameters exceed guidelines at each station, depth and year (F_1).

Firstly, to assess which factor of the equation (F_1, F_2 or F_3) was contributing the most to the overall index, each factor was plotted against each index (Figure 2). Secondly, to assess these relationships statistically, a stepwise regression analysis was performed for each index (Table 7).

Regression analysis revealed that for both DWQI and HWQI, F_3 was the driving factor ($R_2 = -0.925$, $p<0.001$; $R_2 = -0.936$, $p<0.001$ respectively). In comparison, AWQI was driven by F_1 ($R_2 = -0.909$, $p<0.001$). These results suggest that:

1) DWQI and HWQI are significantly influenced by the extent to which parameters exceed the guideline, with little influence of how many parameters fail, or how many times each parameter fails;
2) AWQI is significantly influenced by the number of parameters that exceed the guideline, with little influence of how many times a parameter fails or the extent to which it fails;
3) With regards to DWQI, the importance of F_3 to the HWQI is far greater than the importance of F_1 to AWQI, i.e. the extent by which a parameter exceeds far outweighs the number of parameters in exceedance. This suggests that HWQI, or specifically the parameters contributing to F_3, have a strong influence over the final DWQI result; and
4) F_2 contributes very little to any of the indicators, suggesting that how many times a parameter failed is not an important factor in determining the index value.
5)

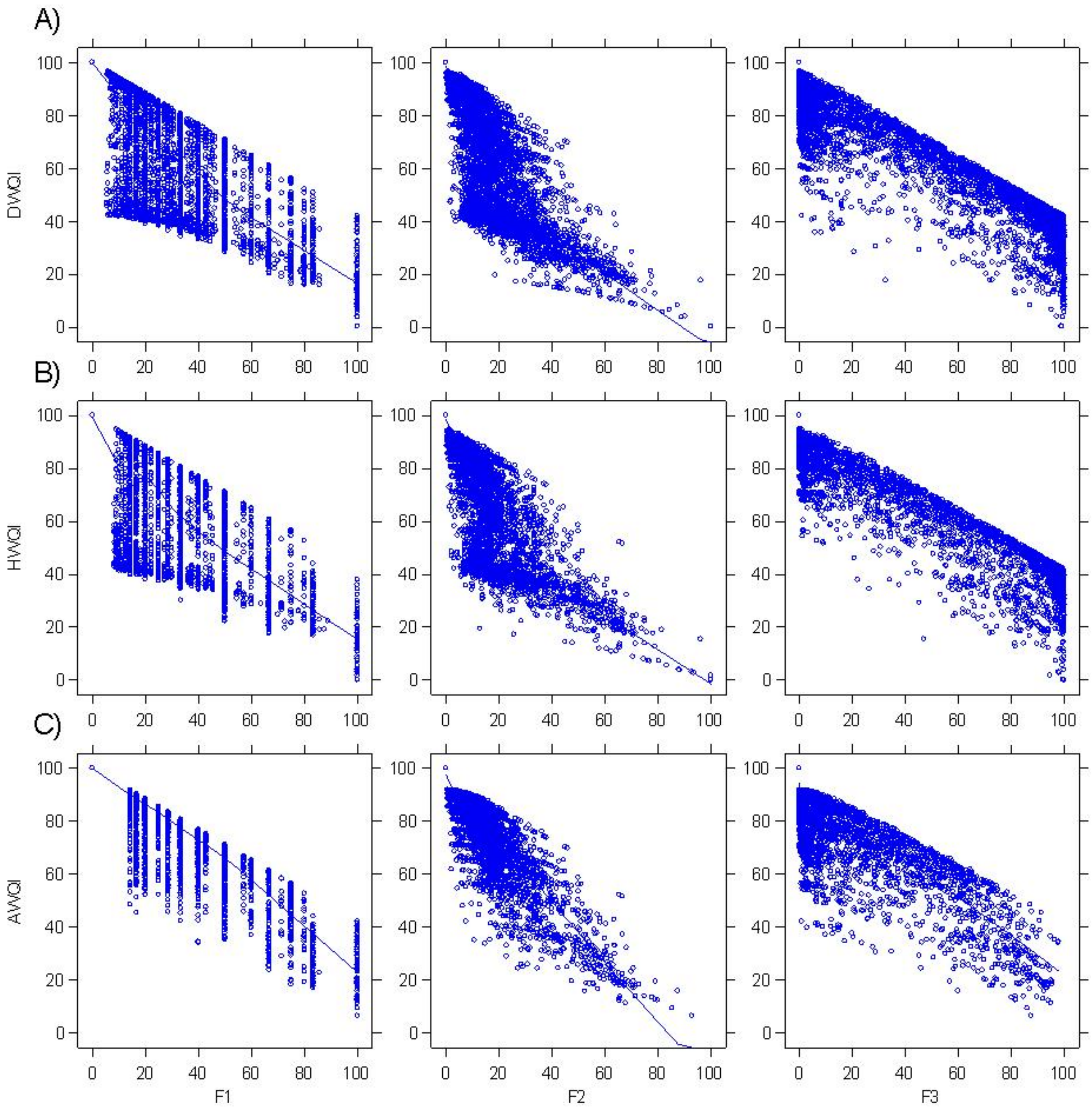

Figure 2: Scatterplots of F_1, F_2 and F_3 against DWQI, HWQI, and AWQI. The fitted lines are locally weighted regression with smoothing parameter = 0.5.

Table 7: Stepwise regression analysis to assess the contribution of F_1, F_2 and F_3 on DWQI, HWQI and AWQI

	Step	1	2	3
DWQI	F_3	-0.925	-0.726	-0.704
	p value	<0.001	<0.001	<0.001
	F_1		-0.411	-0.362
	p value		<0.001	<0.001
	F_2			-0.073
	p value			<0.001
	R^2	0.856	0.985	0.986
HWQI	F_3	-0.936	-0.749	-0.724
	p value	<0.001	<0.001	<0.001
	F_1		-0.382	-0.333
	p value		<0.001	<0.001
	F_2			-0.076
	p value			<0.001
	R^2	0.877	0.988	0.989
AWQI	F_1	-0.909	-0.654	-0.563
	p value	<0.001	<0.001	<0.001
	F_3		-0.469	-0.408
	p value		<0.001	<0.001
	F_2			-0.162
	p value			<0.001
	R^2	0.827	0.981	0.990

Using this information it is possible to determine, in the case of HWQI and DWQI, which parameters had the largest excursion from the guideline, and therefore which parameters were driving the index. It is also possible, in the case of AWQI, to determine which parameters were exceeding the most times, and therefore which parameters were driving the index. This will assist in validating the index against real data and also help in identifying parameters, or guidelines, of concern.

2) Parameter Contributions and Correlation Analysis

To understand which parameters were contributing the most to the index, the parameters that exceeded the guideline within each index were plotted in Figure 3. This figure illustrates which parameters exceeded the guideline (F_1) and the contribution (%) of each parameter to the total number of exceedances, that is, the most common parameters to fail.

Faecal coliform bacteria (FCB), pH and iron account for over 60% of the exceedances observed in the DWQI suggesting that they are the most common, and maybe having the most influence on the index. When this index is broken down into HWQI and AWQI we can see that FCB accounts for over 75% of all exceedances in the HWQI, and, pH and iron account for over 75% in the AWQI which corresponds well with the DWQI exceedances.

To assess the contributions of parameters on each index statistically, correlation analysis was conducted with each parameter against their respective index. A standardised value was required to allow for comparisons among the parameters, and this value was determined to be Excursion Sum and was calculated as follows:

1) (Value/Guideline)-1 = Excursion
2) ∑(Excursions for station year and depth)

Scatterplots for each index against its respective parameters can be seen in Figures 4 to 6. The correlation matrix is shown in Table 8.

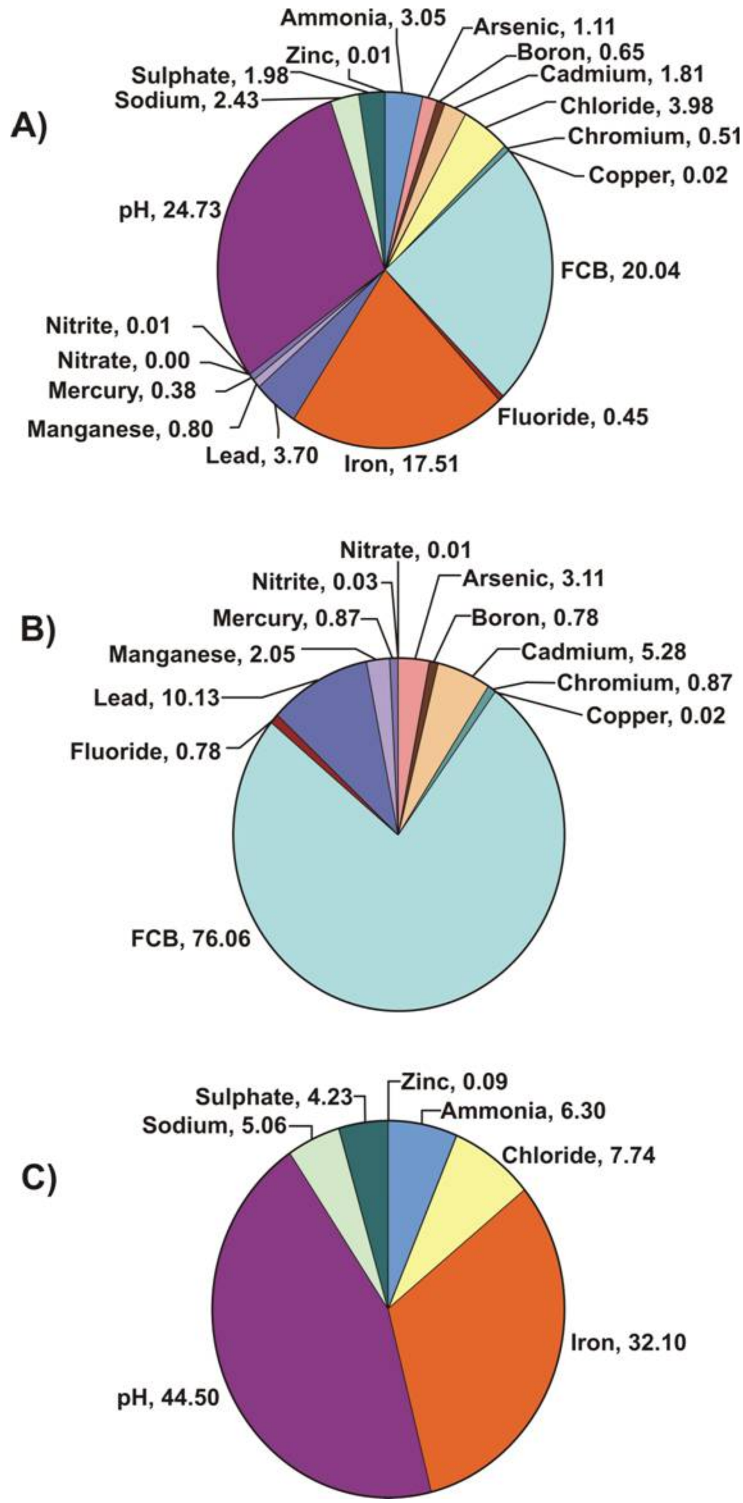

Figure 3: Parameters that exceeded the guideline (percentage of total exceedances) for: A) DWQI, B) HWQI and C) AWQI.

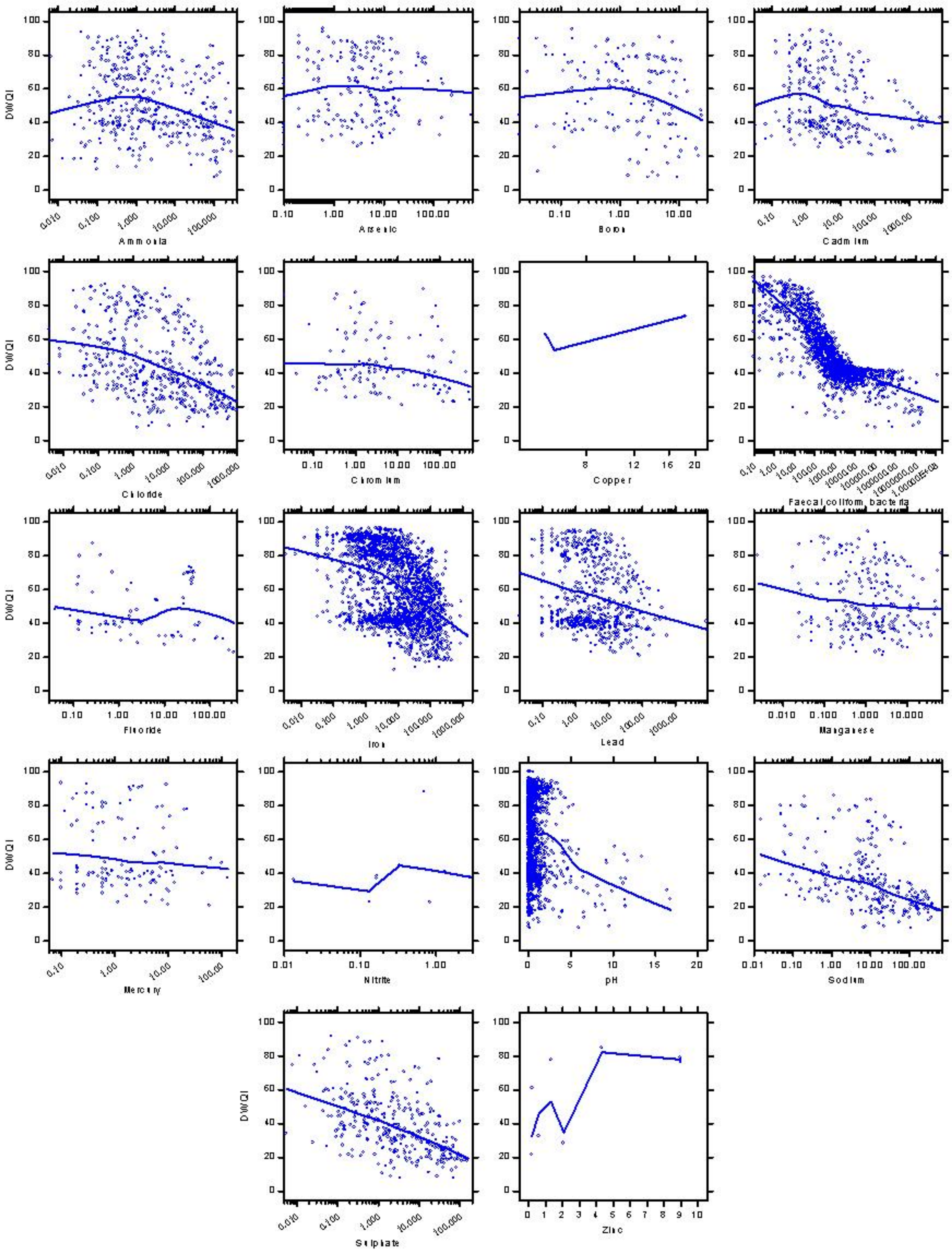

Figure 4: Scatterplots of excursion sums for each exceeded parameter against the DWQI. Lines represent locally weighted regression with smoothing parameter =0.7.

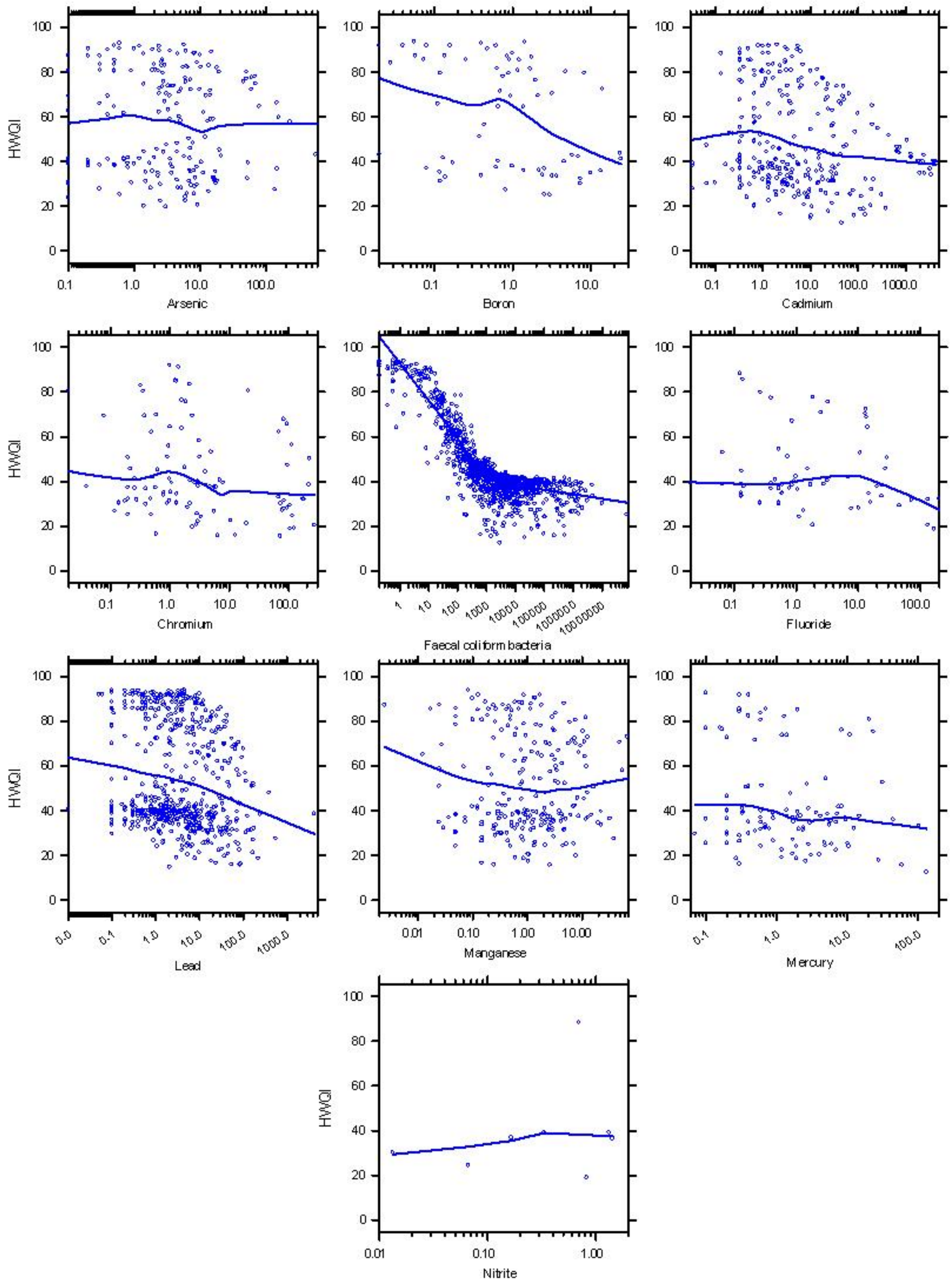

Figure 5: Scatterplots of excursion sums for each exceeded parameter against the HWQI. Lines represent locally weighted regression with smoothing parameter =0.7.

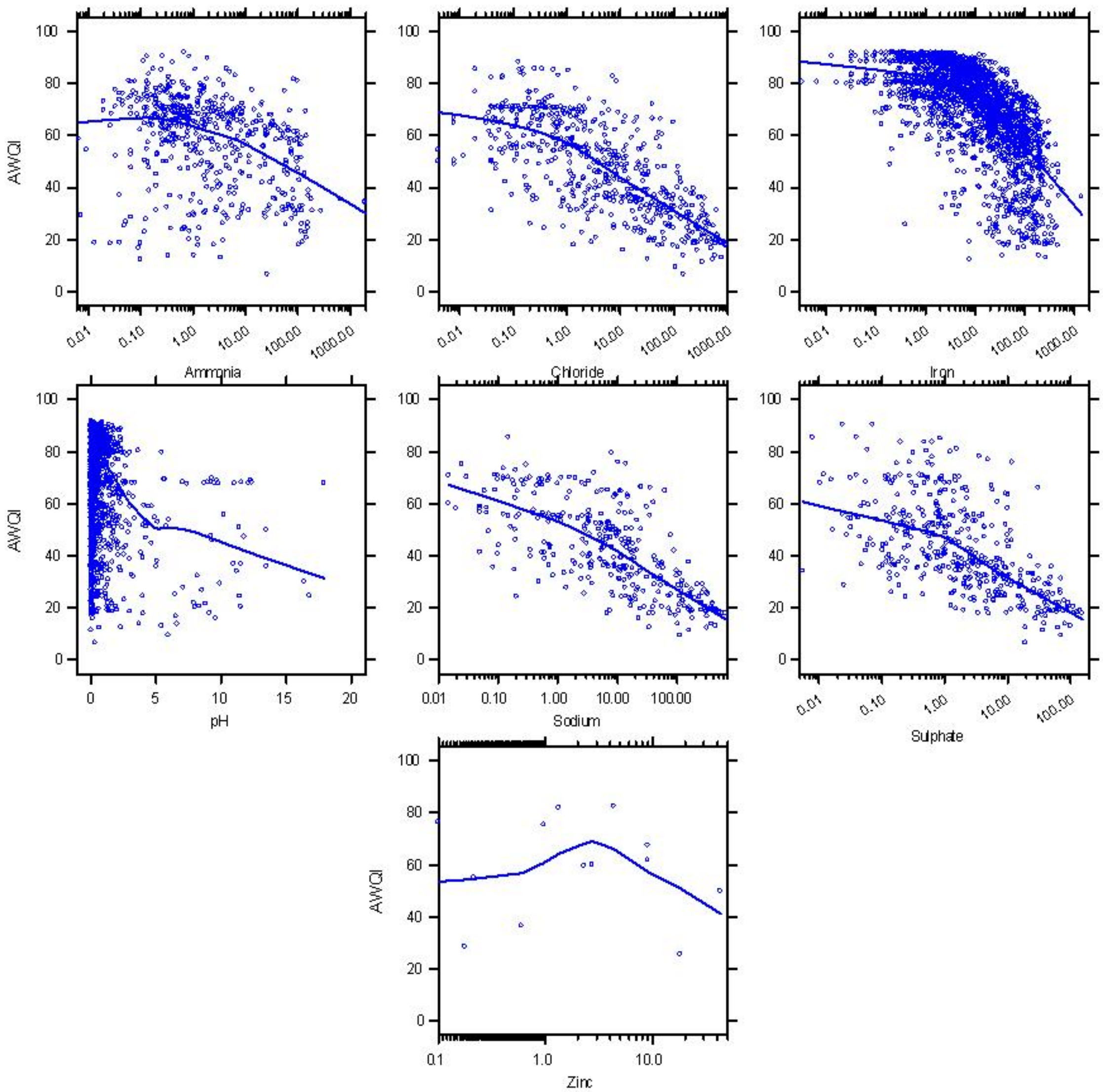

Figure 6: Scatterplots of excursion sums for each exceeded parameter against the AWQI. Lines represent locally weighted regression with smoothing parameter =0.7.

Table 8: Pearsons correlation results for excursion sums (log-transformed, except for pH) of parameters from the guideline, as an average for each station, year and depth against the corresponding DWQI, HWQI and AWQI

PARAMETER	DWQI			HWQI			AWQI		
	n	r	*p*	*n*	*r*	*p*	*n*	*r*	*p*
Ammonia	467	-0.217	<0.001				545	-0.320	<0.001
Arsenic	182	-0.009	0.900	181	-0.061	0.418			
Boron	156	-0.144	0.080	67	-0.342	0.005			
Cadmium	277	-0.239	<0.001	287	-0.224	<0.001			
Chloride	580	-0.422	<0.001				564	-0.715	<0.001
Chromium	117	-0.229	0.013	100	-0.213	0.034			
Copper	3	0.849	0.355						
FCB	2089	-0.800	<0.001	1145	-0.805	<0.001			
Fluoride	78	-0.012	0.919	63	-0.171	0.179			
Iron	2065	-0.435	<0.001				2171	-0.641	<0.001
Lead	603	-0.227	<0.001	599	-0.194	<0.001			
Manganese	239	-0.114	0.084	230	-0.092	0.166			
Mercury	131	-0.105	0.255	112	-0.200	0.035			
Nitrite	2	0.202	0.603	9	0.286	0.456			
pH	2905	-0.204	<0.001				2984	-0.299	<0.001
Sodium	317	-0.439	<0.001				343	-0.698	<0.001
Sulphate	386	-0.493	<0.001				428		
Zinc	8	0.639	0.088				13	-0.258	0.354

Note: n = the number of excursions, r = Pearsons correlation (two-tailed), and p = Bonferroni probabilities.

For the DWQI, the correlation results from Table 8 correspond closely with Figure 3 in that the largest contributors, FCB, pH and iron, are all significantly correlated with the index (r = -0.800, p<0.001; r = -0.204, p<0.001; and r =-0.435, p<0.001 respectively). The HWQI and AWQI also demonstrate consistent correlations compared with both DWQI and the parameters that exceed the most. FCB demonstrates the strongest correlations with HWQI (r=-0.805, p<0.001) and chloride (r=-0.715, p<0.001), sodium (r=-0.698, p<0.001) and iron (r=-0.641, p<0.001) show strong correlations with AWQI.

Conclusions

It is quite clear that FCB strongly influenced the HWQI and DWQI result. This was a concern when this parameter was originally included within the index because of the stringent guideline of 10 counts/100 mL. It would seem that because of the stringent guideline, FCB is consistently in exceedance and far outweighing any other health parameter included in the index equation for both HWQI and DWQI. In addition, analysis of GEMStat data showed that values of FCB are commonly reported in the 1000s and above, which explains why HWQI and DWQI were so heavily influenced by F_3 (the extent to which a parameter exceeds the guideline). Because of these two factors, it was decided that removal of FCB was required from both the HWQI and DWQI calculation and separate assessment of FCB should be conducted. The following assessments are made with the revised HWQI and DWQI that do not include FCB. Separate assessment of FCB will be reported elsewhere once the development of a microbial index is undertaken.

Global Water Quality Index – Revised

Following removal of FCB from HWQI and DWQI, the indices were plotted again on a regional basis, similar to Figure1 (Figure 7). We can see that the trends in the revised indices are much less erratic, and, DWQI follows HWQI and/or AWQI consistently in all regions. This would indicate that the indices are more comparable, that is, they follow similar trends on a global basis, with the removal of FCB. We would conclude, therefore, that our decision to remove FCB and analyse microbial data separately was valid.

Following on from our decision to omit FCB from further index calculations, a sensitivity analysis was required to assess the remaining parameters and their influence over the final index values. The following section (Section 3) describes the sensitivity analysis conducted on HWQI and AWQI on a global basis.

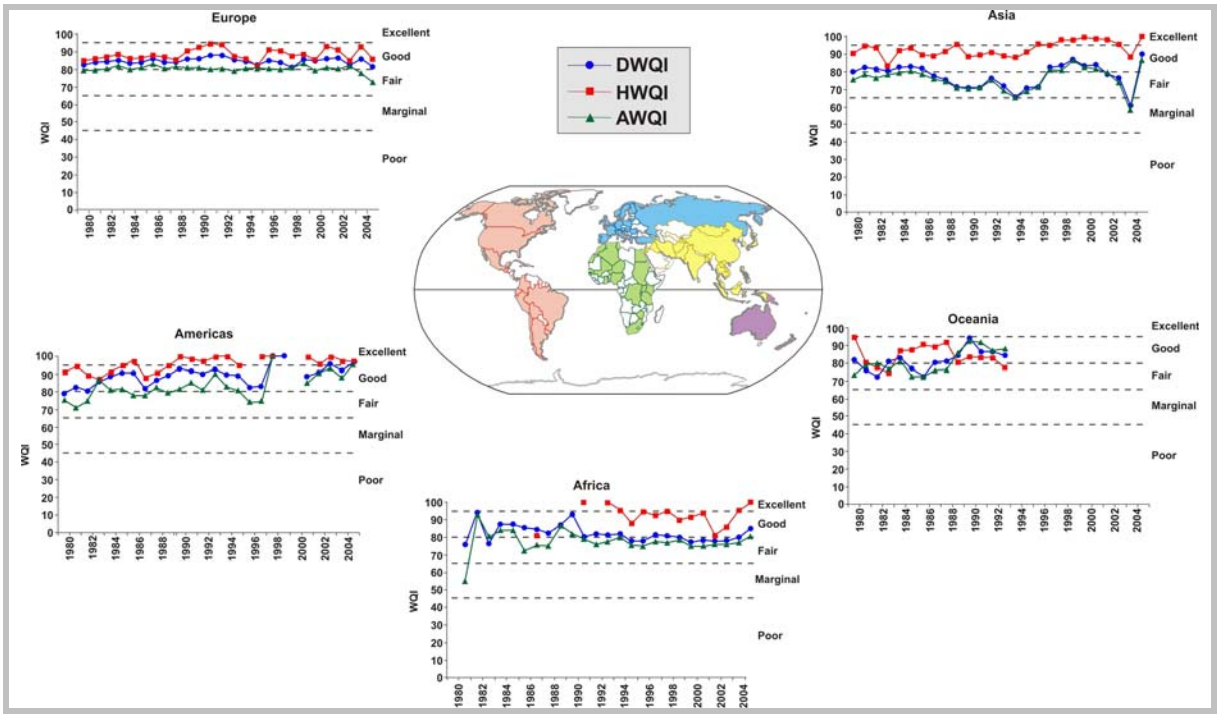

Figure 7: Temporal trends in water quality (DWQI, HWQI and AWQI) for the five regions (Africa, Americas, Asia, Europe and Oceania). Note that indices here were calculated without FCB. Data represent annual averages for each region.

3) Sensitivity Analysis

To investigate the influence of the significant parameters outlined in Table 8 (excluding FCB), sensitivity analysis was conducted. This entailed removing each parameter from the index calculation and comparing the indices to the original. The objective was to observe whether or not any one parameter changed the index so much that it was no longer correlated with the original indices. This is a particularly useful tool in assessing HWQI now that FCB is no longer included.

Analysis of stations globally was conducted to assess the HWQI and AWQI. DWQI was omitted from this analysis as both HWQI and AWQI demonstrated such similar performance to DWQI, in that any parameters influencing HWQI or AWQI will also influence DWQI.

We looked at all stations for the year 2002, and this year was selected based on the amount of data available for all stations, since adequate data from numerous stations globally was required to conduct the analysis. It was also the most recent dataset with an optimal amount of data for analysis.

Firstly, we compared HWQI with AWQI and categorised water monitored at the stations into poor-to-excellent designations (Figure 8). The data are presented as a percentage of total stations that had an index value calculated in 2002 globally. A total of 68 stations had an HWQI designation and 144 stations had an AWQI designation in 2002. The countries for which there was an HWQI and AWQI are shown in Table 9.

Table 9: Number of stations, listed by country, for which an HWQI and AWQI were calculated for the year 2002

Country	HWQI	AWQI
Morocco	6	6
Argentina	5	7
Japan	11	13
Republic of Korea	1	1
Belgium	37	18
Poland	6	6
Switzerland	2	6
South Africa	-	24
India	-	24
Pakistan	-	5
Russian Federation	-	34

In the year 2002, water from approximately 45% of stations was classed as excellent and water from approximately 25% was classed as good for health aspects (HWQI) (Figure 8). Less than 2% of stations with an HWQI were classed as poor. For AWQI, approximately 30% of stations were classed as good with less than 15% of stations classed as excellent. The majority (40%) of stations were classed as fair in 2002 (Figure 8).

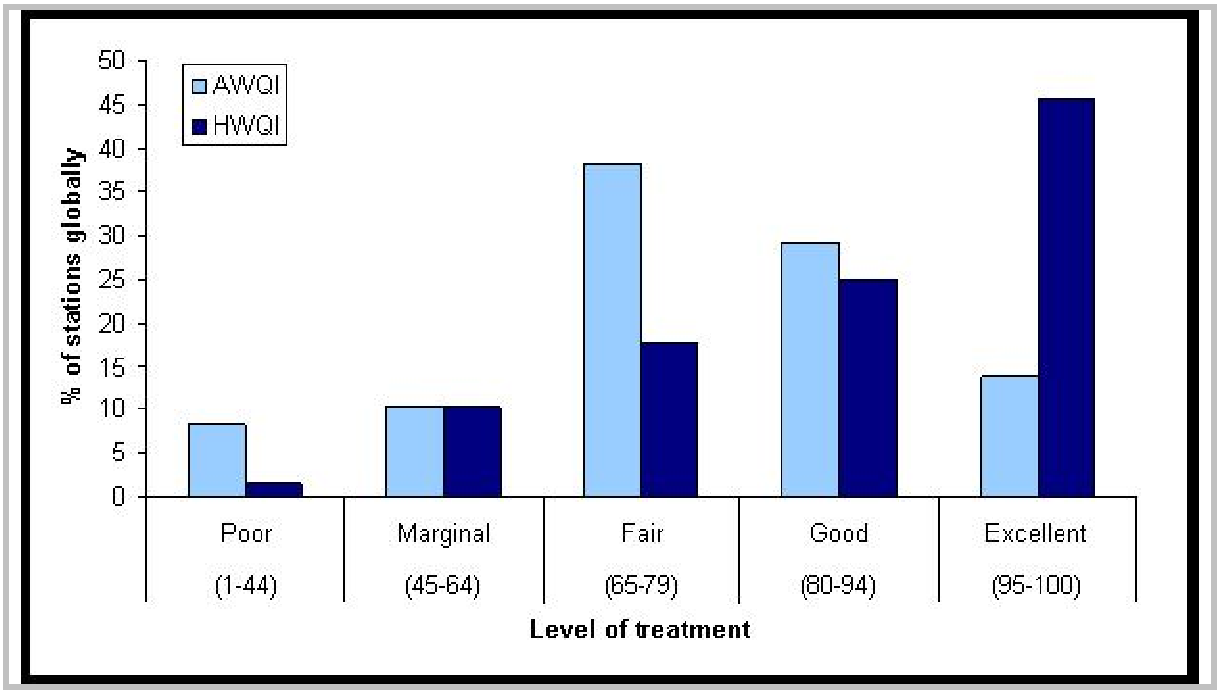

Figure 8: The number of stations (percentage of total stations globally) in 2002, categorised as poor, marginal, fair, good and excellent for both HWQI and AWQI.

To determine which parameters were possibly driving each index, the parameters contributing to each index (Table 10) were selected for the sensitivity analysis. To conduct a sensitivity analysis, each of the parameters was removed and the HWQI and AWQI recalculated and plotted against the original index (Figures 9 and 10). This makes it possible to observe which parameter most influences each index.

Table 10: Parameters included in both HWQI and AWQI sensitivity analysis for 2002

HWQI	AWQI
Arsenic	Ammonia
Boron	Chloride
Cadmium	Iron
Chromium	pH
Fluoride	Sodium
Lead	Sulphate
Manganese	
Mercury	

AWQI

For AWQI (Figure 9), the removal of pH increased the number of stations designated as excellent from approximately 15% to 50%. When the data were analysed statistically (Table 11), all indices were significantly correlated regardless of which parameter was removed. pH showed the least strong correlation to AWQI which follows the pattern expected from Figure 9; however, the relationship is still significant.

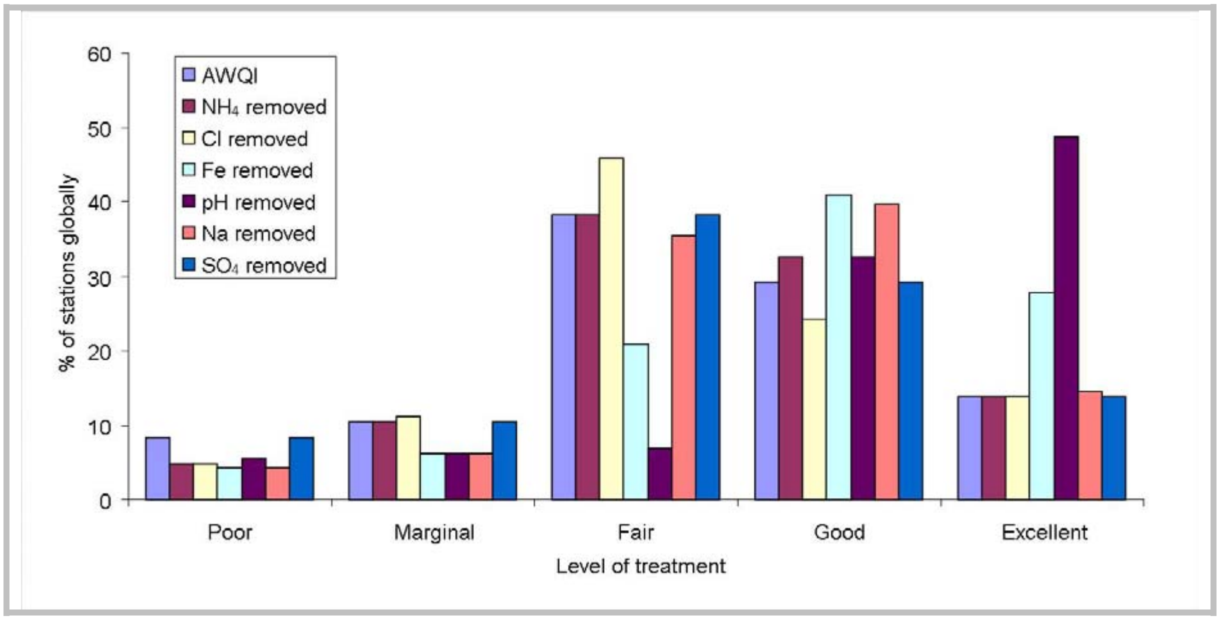

Figure 9: Designation of stations in 2002 (displayed as a percentage of the total number of stations [n=144]) and the contributions of each parameter to the AWQI.

Table 11: Pearsons correlation matrix for AWQI sensitivity analysis

	AWQI	NH_4 removed	Cl removed	Fe removed	Ph removed	Na removed	SO_4 removed
AWQI	1.000						
NH_4 removed	0.954	1.000					
Cl removed	0.924	0.942	1.000				
Fe removed	0.866	0.864	0.864	1.000			
Ph removed	0.832	0.857	0.783	0.701	1.000		
Na removed	0.944	0.958	0.943	0.865	0.844	1.000	
SO_4 removed	0.982	0.965	0.944	0.872	0.849	0.951	1.000

HWQI

For HWQI (Figure 10), the removal of lead and arsenic had the most impact on station designations. Removal of arsenic, similar to the original HWQI, reduced the amount of poor, marginal and fair results and increased the amount of stations designated good from 24% to over 42%. Removal of lead reduced the amount of stations designated good and increased the amount of excellent from 45% to 63%. However, the removal of these parameters did not significantly change the HWQI designations and correlation analysis revealed that these positive relationships were all significant and none of the parameter removal reduced the r value <0.9 (Table 12). We would conclude that no one parameter is influencing the overall HWQI, suggesting that the index value is robust regardless of the parameters that are included.

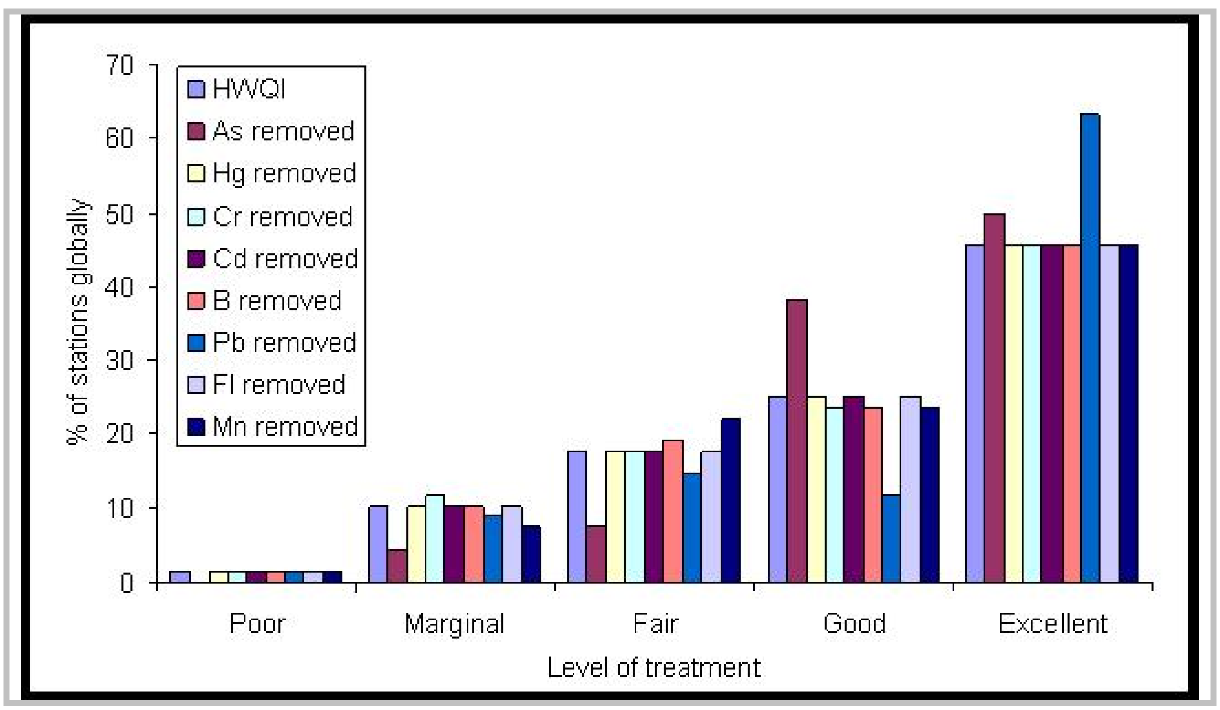

Figure 10: Designation of stations globally in 2002(displayed as a percentage of the total number of stations [n=68]) and the contributions of each parameter to the HWQI.

Table 12: Pearson's correlation matrix for HWQI sensitivity analysis

	HWQI	As removed	Hg removed	Cr removed	Cd removed	B removed	Pb removed	Fl removed	Mn removed
HWQI	1.000								
As removed	0.963	1.000							
Hg removed	0.999	0.959	1.000						
Cr removed	0.999	0.959	0.998	1.000					
Cd removed	0.998	0.952	0.997	0.998	1.000				
Bo removed	0.998	0.959	0.998	0.999	0.998	1.000			
Pb removed	0.975	0.935	0.977	0.971	0.967	0.969	1.000		
Fl removed	0.998	0.972	0.996	0.996	0.994	0.996	0.976	1.000	
Mn removed	0.996	0.955	0.995	0.998	0.997	0.997	0.965	0.992	1.000

Conclusions from Sensitivity Analysis

The Pearson's correlation matrix for both HWQI and AWQI (Table 11 and 12) revealed that regardless of which parameter was removed, the indices were still significantly correlated. This suggests that both indices are not strongly driven by one particular parameter, but rather by the combination of all parameters. The observation for AWQI compare well with our previous sensitivity analysis, with F_1, F_2 and F_3, where we observed that the number of parameters exceeding the guideline (F_1) was influencing the final index value. With FCB removed it would seem that, similar to AWQI, no one parameter is influencing the final HWQI value which supports our decision to remove FCB from the index calculation.

Conclusions

Overall, using the WHO water quality guidelines for drinking water was adequate for selecting appropriate parameters to include in the index, with the exception of FCB. The types of guidelines, such as health and acceptability, were used to separate the overall DWQI into two further indices allowing a more accurate interpretation of water quality globally. Analysis of parameters influencing the index value demonstrated that both DWQI and HWQI were strongly driven by the extent to which a parameter exceeded the guideline whereas AWQI was strongly driven by how many parameters exceeded the guideline. We concluded that HWQI and DWQI were strongly influenced by FCB, and, as such this parameter was removed from the index calculation to be assessed separately. Once FCB was removed, a sensitivity analysis was conducted with both HWQI and AWQI and we concluded that no one parameter was influencing, i.e. changing, the final index value significantly.

When the indices were plotted on a regional basis, AWQI and HWQI followed DWQI only in some regions, and when one did, the other did not. This adds weight to our decision to split the overall index (DWQI) into two, allowing us to observe what types of parameters (health or acceptability) are responsible for the index value.

The results of our analysis would indicate that the indices are reflective of the real data as they demonstrated strong correlations to a number of parameters included within the calculation. We would conclude that the use of the indices will be reflective of real data and will provide a useful tool in assessing water quality on a regional, national or watershed level.

To assess the indices on a watershed scale, a case study was conducted using data from the Vistula River, Poland. This analysis is described in Chapter 5.

Chapter 5

Vistula River, Poland: Case Study

An assessment of the Vistula River data was conducted to determine the usability of the designations both on a temporal and spatial scale (upstream to downstream), and to attempt to validate the indices (DWQI, HWQI and AWQI).

The Vistula River is the longest river in Poland, spanning 1,047 km and draining an area of 194,424 km². The direction of flow of the Vistula is from south to north, originating at Barania Góra (1,220 m high) in the Beskidy Mountains. It flows through several large Polish cities along its way, including:

- ***Kraków:*** Station 021003, located at Solid Weir "Kosliuszko", upstream of Kraków. Upstream site;
- ***Warsaw***: Station 021002 located at Lazienkowski Bridge, within the city of Warsaw. Midstream site; and
- ***Tczew***: Station 021001, located at the Kiezmark Bridge downstream of Tczew. Downstream site.

The Vistula empties into the Vistula Lagoon and Gdańsk Bay of the Baltic Sea (Figure 11).

Our first objective was to assess the water quality (overall, health and acceptability) of the Vistula River over time. An overview of the temporal trends of all three indices at each station on the Vistula River is illustrated in Figure 11.

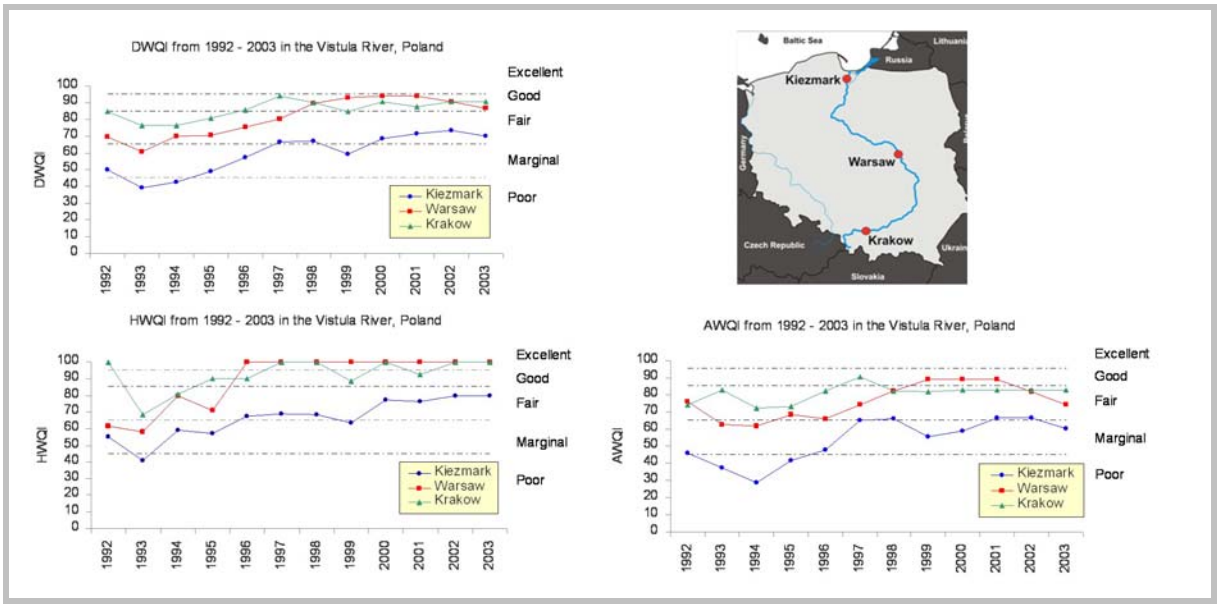

Figure 11. DWQI, HWQI and AWQI at three sites along the Vistula River (Kiezmark, Warsaw and Kraków) between 1992 and 2003.

The trends in DWQI, HWQI and AWQI correspond well at each site along the Vistula River. This is especially true at Kiezmark and Kraków where the trends over time are very similar. The water quality at Warsaw is excellent for HWQI but marginal to good for AWQI. As a result, the DWQI falls in between the two resulting in a fair-to-good rating.

Over time there is some improvement in water quality, since at all three sites, the DWQI shows a general increase in index values. A similar trend can be seen with HWQI but this trend is a little less clear. However, AWQI suggests little change over time (Figure 11).

To illustrate more clearly how the Vistula River water quality changed spatially and temporally, that is, from upstream to downstream, colour coding was applied to the designations. For our purposes the HWQI and AWQI were used. A map of the Vistula River has been reproduced in Figure 12 to illustrate three time points 1992, 1997 and 2003. The H box represents HWQI and A represents AWQI, and the colours correspond to the designations: poor (red), marginal (orange), fair (yellow), good (green), and excellent (blue).

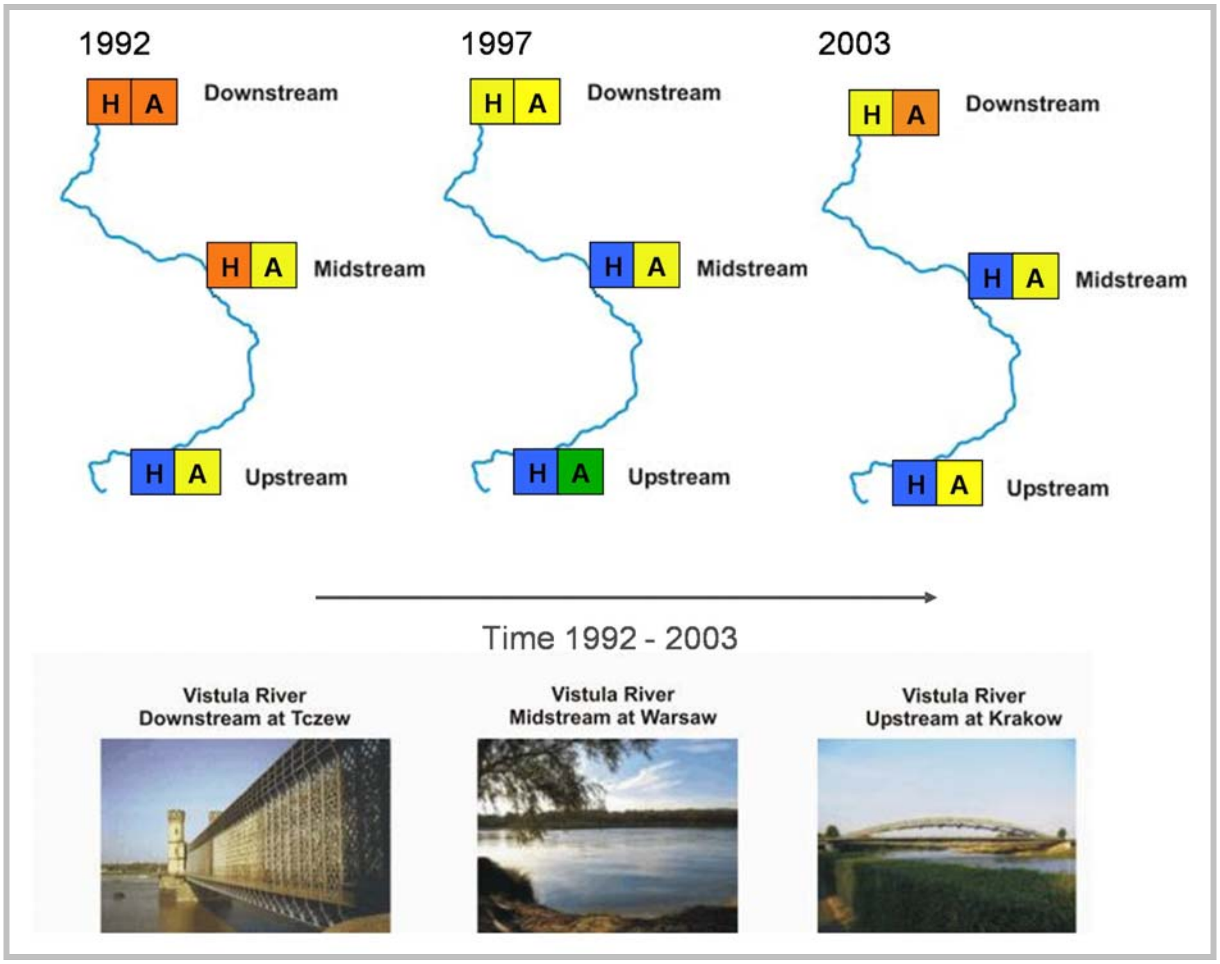

Figure 12: Temporal trends in DWQI, HWQI and AWQI in the Vistula River, Poland from 1992 -2003. The H and A boxes represent HWQI and AWQI respectively, and the colours correspond to index designations:: poor (red), marginal (orange), fair (yellow), good (green), and excellent (blue).

Two clear patterns were observed in Figure 12:

1) Spatial: at each time point the quality of water improved from downstream (Kiezmark) to upstream (Krakow) indicating that the intensity of treatment required for drinking also decreased between Kiezmark and Kraków; and
2) Temporal: over time the quality of water, with respect to health parameters, improved in the downstream and midstream sites. The quality of water, with respect to acceptability, improved from 1992 to 1997, however, this improvement did not persist through to 2003.

Using the colour coded designations both spatial and temporal observations of water quality within the Vistula River can be made. This demonstrates the usefulness of the designations and the potential for graphical illustration of water quality for both health and acceptability.

To assess the validity of the index results analysis was conducted to compare the real data against their respective index values at each station over time.

Validation of the indices

To understand the temporal patterns occurring with the indices, we first had to establish which parameters were contributing to each index 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 is divided into individual sites: 1) Kiezmark (downstream), 2) Warsaw (midstream) and 3) Kraków (upstream). Each section describes the parameter selection and correlation analysis for all three indices.

1. Kiezmark – Station 021001

The first step was to determine which parameters were in exceedance of each guideline and then plot them according to their percentage contribution, that is, percentage of total exceedances in that year (Figure 13).

The HWQI and AWQI have a number of parameters that are consistently in exceedance at this site. Lead and cadmium are exceeding in all years in the HWQI, with mercury exceeding between 1992 and 1995. Chloride, ammonia and sodium are exceeding in all years in the AWQI with Iron in exceedance between 1992 and 1996. When these indices are combined into the DWQI the same parameters are in exceedance suggesting that the DWQI is an accurate reflection of both HWQI and AWQI combined.

The parameters that were consistently in exceedance for each index were selected for correlation analysis with the indices. The annual averages of each of these parameters were plotted against their respective guideline and index (Figures 14 to 16), and assessed statistically using Pearsons correlation analysis. These results are shown in Table 13.

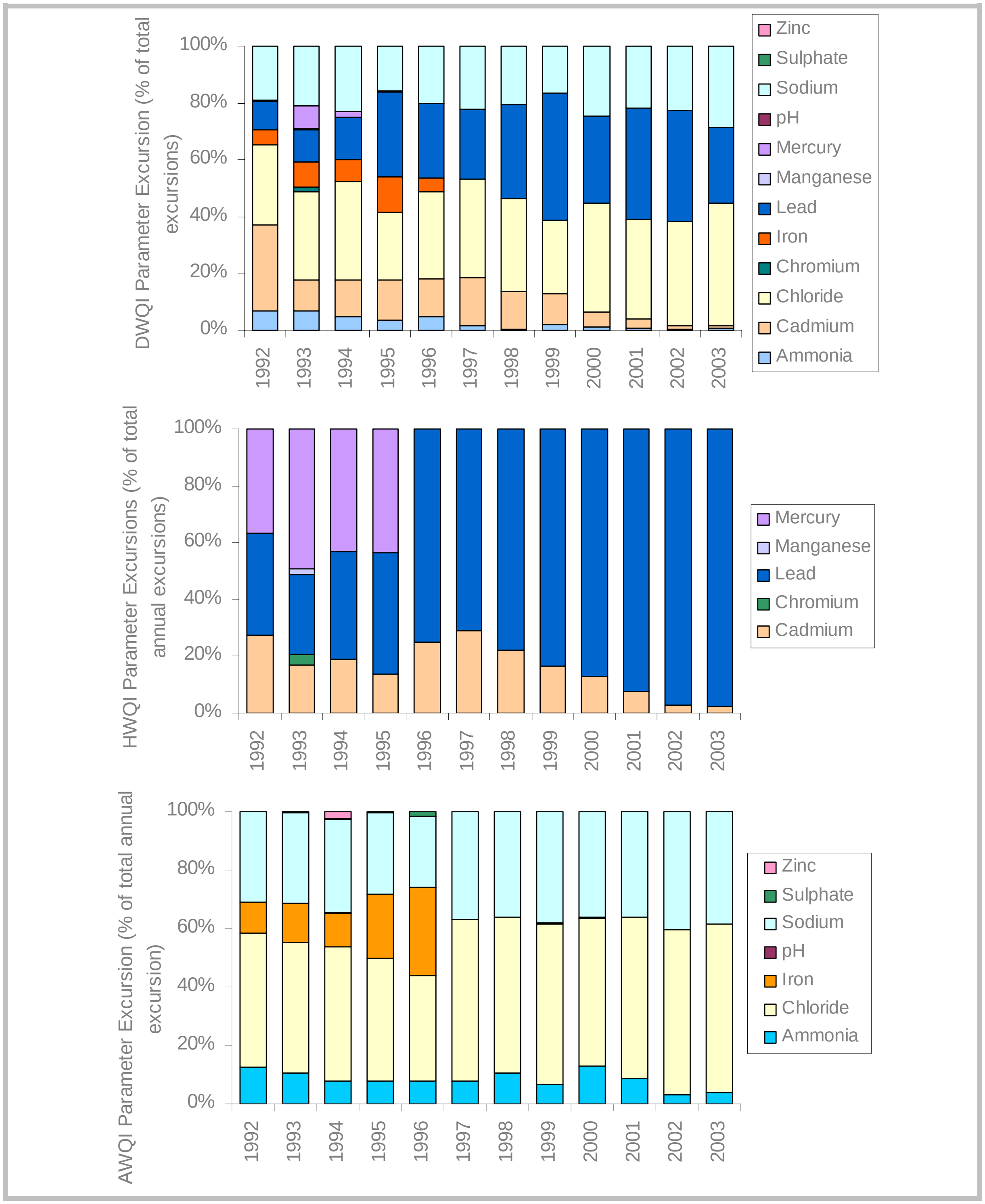

Figure 13: Parameter excursions for Kiezmark (Station 021001), as a percentage of total excursions per annum, for DWQI, HWQI and AWQI.

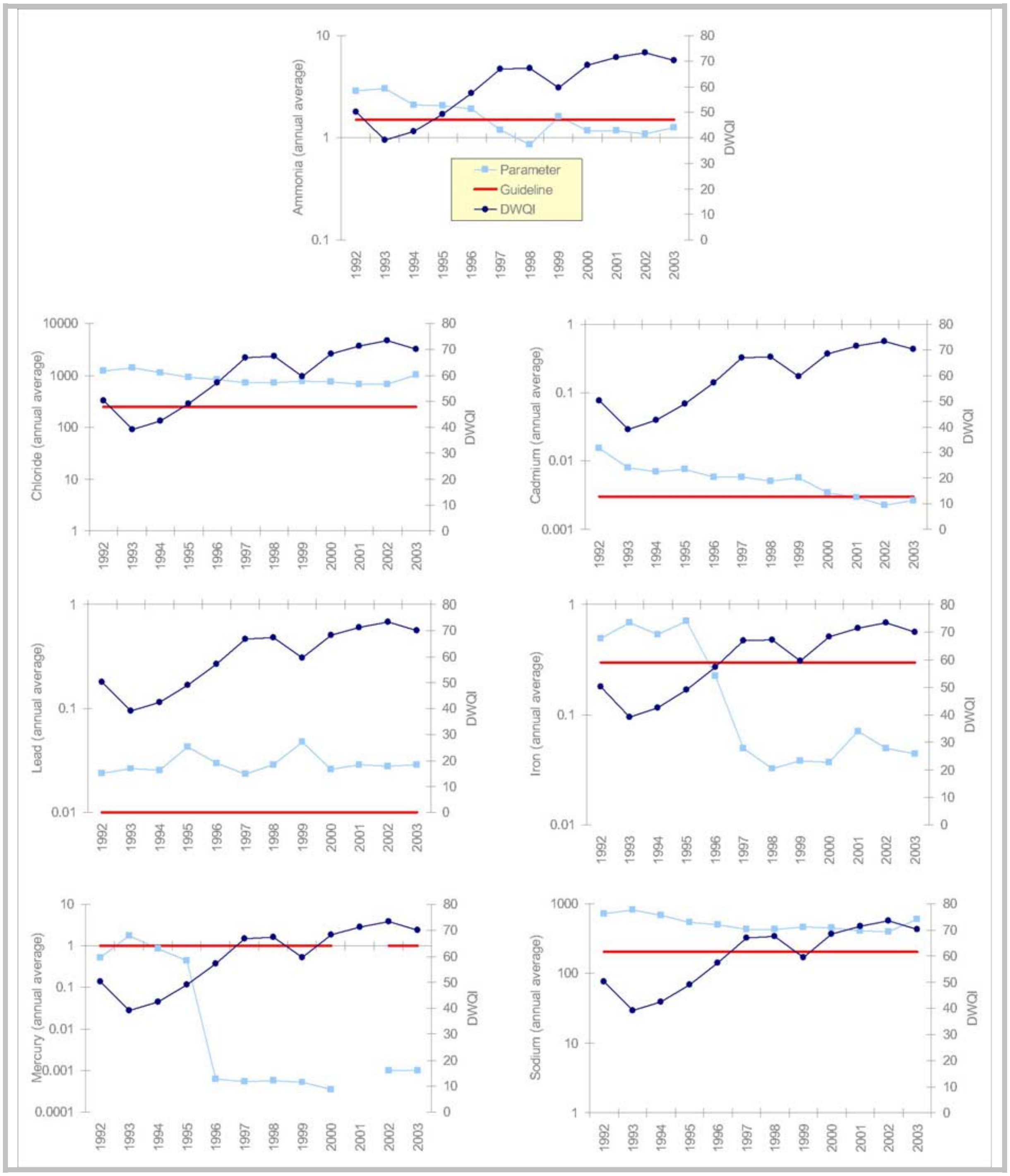

Figure 14: Annual averages (log scale) of each parameter, their respective guideline and associated DWQI for Kiezmark Station 021001 from 1992 to 2003.

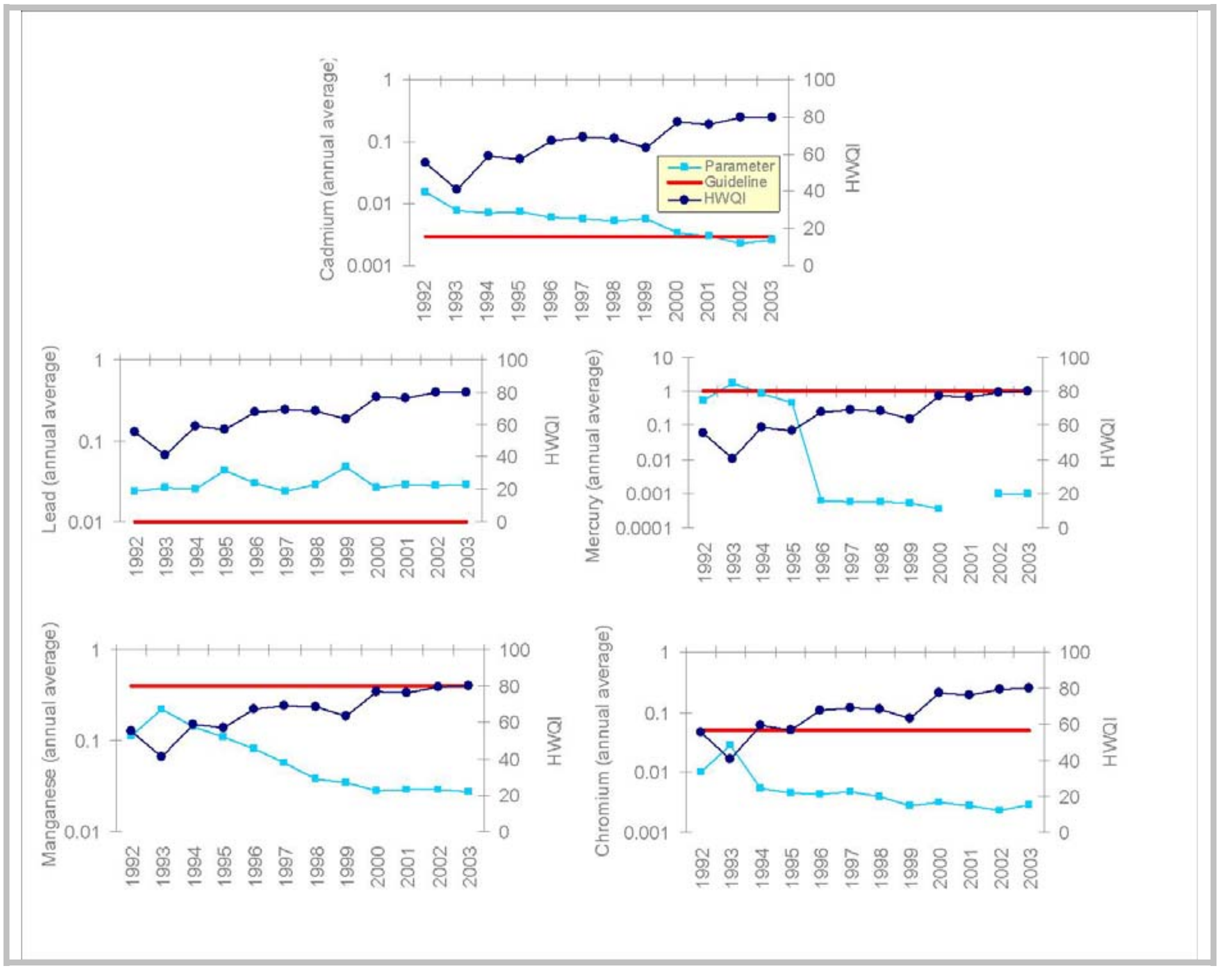

Figure 15: Annual averages (log scale) of each parameter, their respective guideline and associated HWQI for Kiezmark Station 021001 from 1992 to 2003.

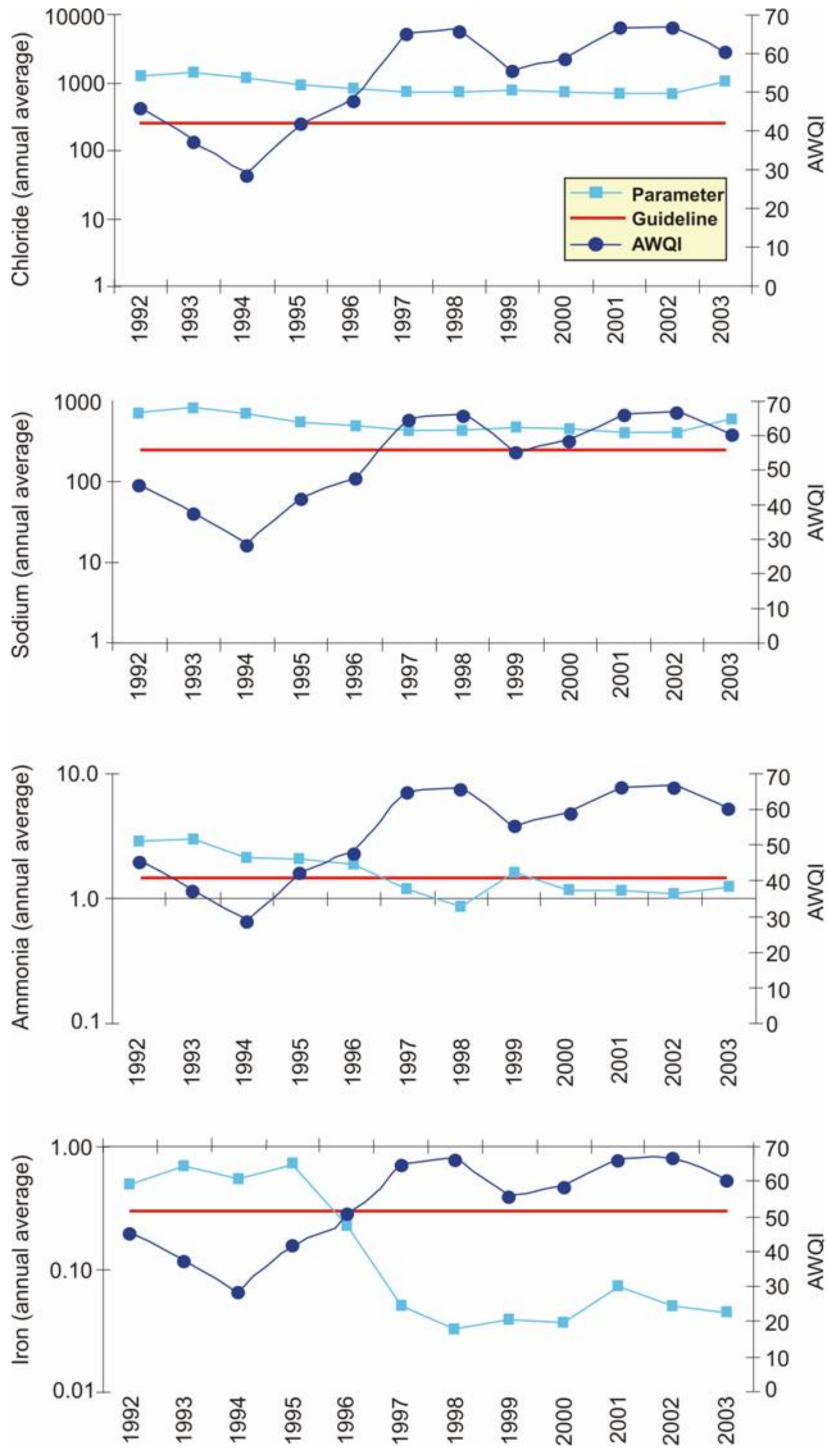

Figure 16: Annual averages (log scale) of each parameter, their respective guideline and associated AWQI for Kiezmark Station 021001 from 1992 to 2003.

As shown in Table 13, the correlation analysis revealed strong relationships between the raw data and the index over time. Specifically, ammonia, chloride, iron and sodium were all significantly correlated with AWQI ($r = -0.863$, $p<0.01$; $r = -0.813$, $p<0.05$; $r = -0.887$, $p<0.01$; and $r = -0.811$, $p<0.05$ respectively). For HWQI, chromium, manganese and mercury were significantly correlated with the index ($r = -0.805$, $p <0.05$; $r = -0.864$, $p<0.01$; and $r = -0.864$, $p<0.01$ respectively). Although cadmium was not significantly correlated ($r = -0.705$, $p=0.231$), it still demonstrated a good relationship with HWQI.

When the two indices are combined into the DWQI we observe similar significant results. Ammonia, chloride, iron, mercury and sodium are all significantly correlated ($r = -0.902$, $p<0.01$; $r = -0.831$, $p<0.05$; $r=-0.916$, $p<0.01$; $r=-0.855$, $p<0.01$; and $r = -0.828$, $p<0.05$).

Table 13: Pearsons correlation matrix for DWQI, HWQI and AWQI against the contributing parameters at Kiezmark (Station 021001)

	DWQI	HWQI	AWQI
Ammonia	-0.902**		-0.863**
Cadmium	-0.687	-0.705	
Chloride	-0.831*		-0.813*
Chromium		-0.805*	
Iron	-0.916**		-0.887**
Lead	-0.078	-0.093	
Manganese		-0.911**	
Mercury	-0.855**	-0.864**	
Sodium	-0.828*		-0.811*

Note: Asterisk represents significant correlation in which:
** = p<0.05, ** =p<0.01 and *** = p<0.001.*

Looking at the real data compared to the indices for AWQI, the drop between 1992 to 1994 was a result of iron, ammonia, sodium and chloride all exceeding their respective guidelines. The rise in AWQI from 1994 onwards was due to the concentration of iron and ammonia being below guideline values. Sodium and chloride are continually in exceedance from 1992 to 2003 and are the two key factors that are keeping the AWQI reaching a near perfect score (95-100) which would indicate an excellent rating.

When we look at the Kiezmark station with respect to its geographical position compared to the other two sites, it is classed as a downstream site. As such, the consistently higher than guideline values for sodium and chloride could merely be due to the natural salinity gradient, that is, the natural increase in dissolved salts from headwater to estuary. However, the higher salt content may also be a result of the hard coal mines in southern Poland that discharge into the upper part of the Vistula River. Kowalkowski *et al.* (2007) report that the salt load from the mines, contains approximately 9,000 tons of sulphates and chlorides per day, two thirds of which are carried off by the Vistula River. It is beyond the scope of this report to make any conclusions regarding the source of chlorides in the river; however, it is important to note that whether the source is from the coal mines, or simply a natural salinity gradient, the AWQI was able to reflect this situation.

The ammonia concentrations of Kiezmark were decreasing throughout the monitoring period with a concentration of 1 – 1.25 mg L^{-1} in 2002 and 2003 compared to 2.8 mg L^{-1} and 3.02 mg L^{-1} in 1992 and 1993. The concentration of ammonia at Kiezmark may be an indication of sewage contamination or inputs which have been reported in this area. Buszewski and Kowalkowski

(2003) report that 85% of river intake returns to the river as sewage. Again, it is beyond the scope of this report to investigate the source of contaminants within the river, however, similar to sodium and chloride, the AWQI is reflective of this issue.

Interestingly, metals were the main parameters in exceedance in the HWQI results. We can see that over time HWQI improves and this is in direct response to a reduction in concentrations of manganese, chromium, mercury and cadmium. Our results are reflective of other results reported in the literature. For instance, large concentrations of heavy metals including cadmium, lead and chromium have been reported in the Bay of Gdansk, and were attributed to the direct discharge of the Vistula River (Pempkowiak *et al.*, 2006). Beldowski and Pempkowiak (2007) also report the Vistula River as the main source of mercury into the Gdansk bay.

When the two indices are combined, we observe exactly the same results indicating DWQI is representative of both. However, the temporal pattern of AWQI and HWQI are reflective of very different issues within the river. AWQI is reflective of the salinity and ammonia issues, and HWQI is reflective of metal contamination.

We would conclude that the separation of DWQI into the two indices was useful in reflecting specific issues of concern. The indices were also reflective of the real data demonstrating good correlations with parameters in exceedance of their respective guideline. Our results and data are reflective of previous studies conducted on the Vistula River.

2) Warsaw – Station 021002

The parameters that exceeded the guideline at Warsaw are illustrated in Figure 17. Again, we can see that for AWQI and HWQI a few parameters are consistently in exceedance . For HWQI lead is the predominant parameter in exceedance, for AWQI, iron, pH and chloride are consistently in exceedance. Interestingly, no exceedances were measured past 1998 in HWQI resulting in an excellent rating.

The annual averages of these parameters were then plotted against their respective guideline for each index (Figures 18 to 20) and the Pearsons correlation results are shown in Table 14.

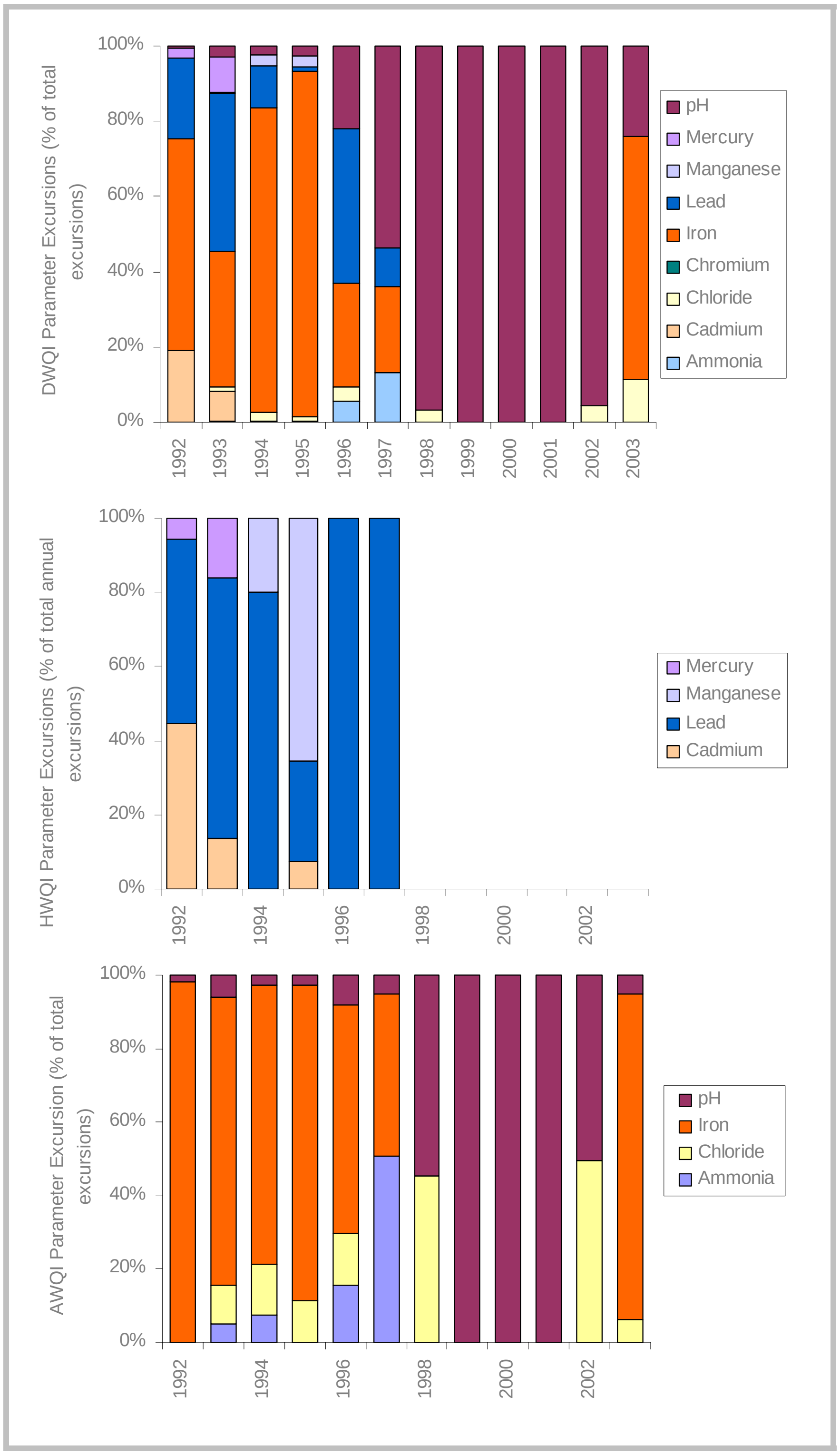

Figure 17: Parameter excursions for Warsaw (Station 021002), as a percentage of total excursions per annum, for DWQI, HWQI and AWQI.

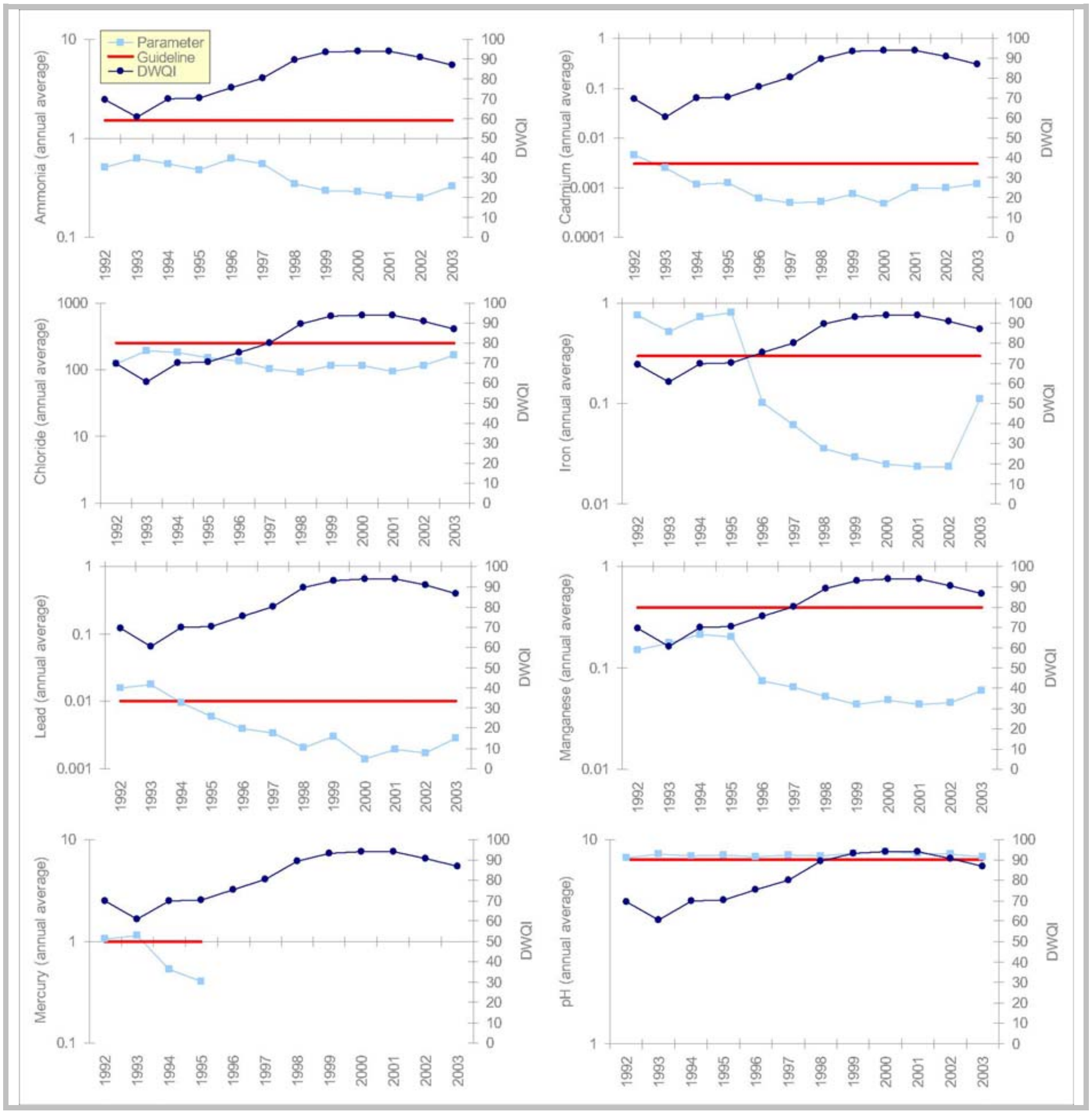

Figure 18: Annual averages of each parameter, their respective guideline and associated DWQI for Warsaw, Station 021002 from 1992 to 2000.

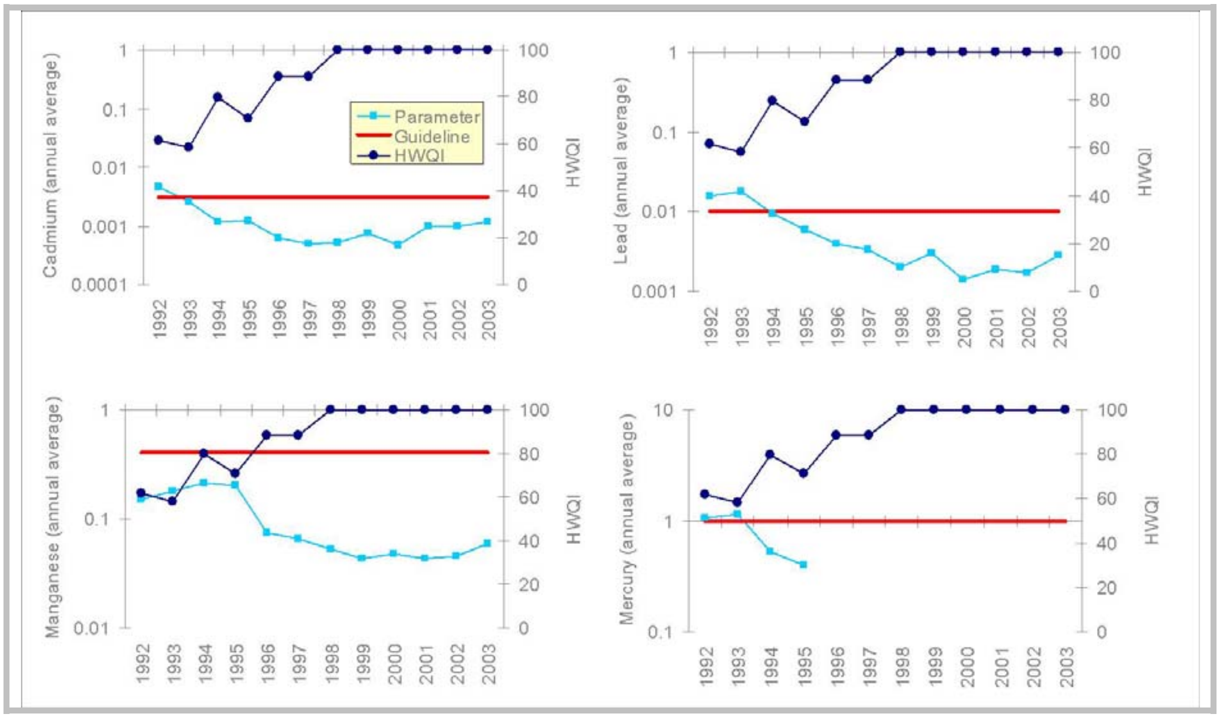

Figure 19: Annual averages of each parameter, their respective guideline and associated HWQI for Warsaw, Station 021002 from 1992 to 2003.

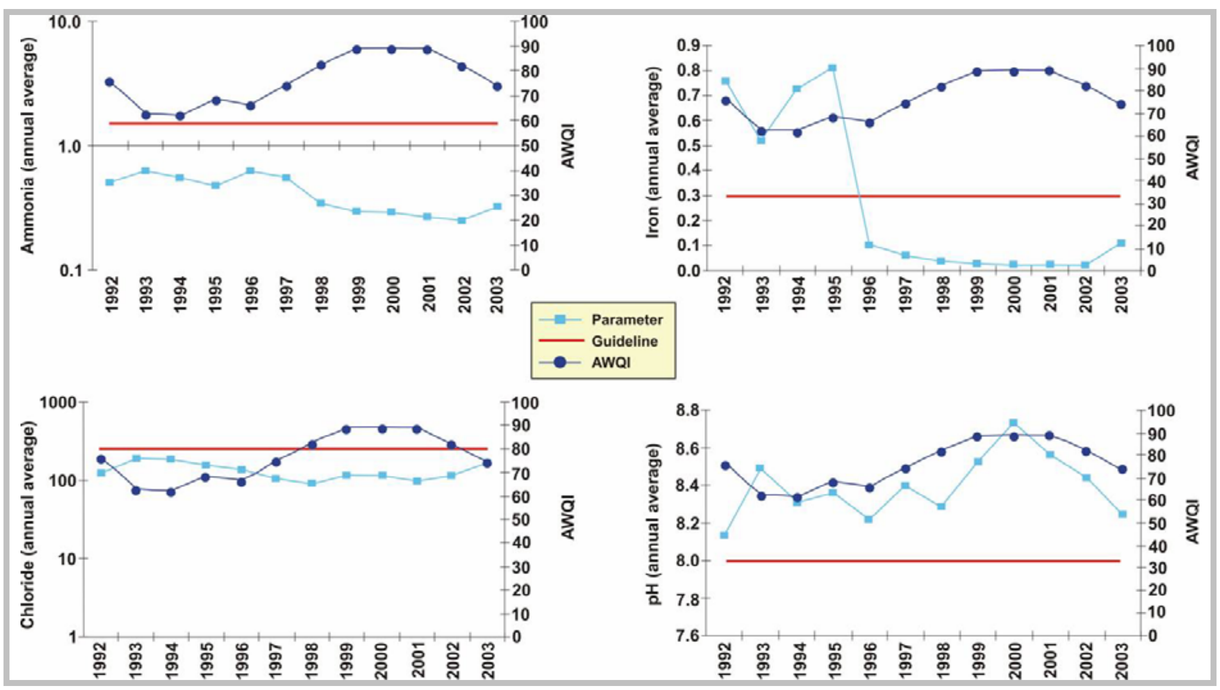

Figure 20: Annual averages of each parameter, their respective guideline and associated AWQI for Warsaw, Station 021002 from 1992 to 2003.

Table 14: Pearsons correlation matrix for DWQI, HWQI and AWQI against the contributing parameters at Warsaw (station 021002)

	DWQI	HWQI	AWQI
Ammonia	-0.894**		-0.866**
Cadmium	-0.580	-0.758*	
Chloride	-0.724		-0.797*
Iron	-0.829*		-0.815*
Lead	-0.856*	-0.929***	
Manganese	-0.879**	-0.850**	
Mercury	-0.690	-0.863	
pH	-0.469		-0.534

*Note: Asterisk represents significant correlation in which: where * = $p<0.05$, ** =$p<0.01$ and *** = $p<0.001$.*

Cadmium, lead and manganese were all significantly correlated with HWQI ($r = -0.758$, $p<0.05$; $r = -0.929$, $p<0.001$; and $r = -0.850$, $p<0.01$ respectively). The correlation with mercury was not significant; however, a good relationship was still observed ($r = -0.863$, $p = 0.137$). This non-significant result is probably due to the lack of data after 1995. Ammonia, chloride and iron were all significantly correlated with AWQI ($r = -0.866$, $p<0.01$; $r = -0.797$, $p<0.05$; and $r = -0.815$, $p<0.05$). pH was not significantly correlated with AWQI even though it was in exceedance of the maximum guideline at various times throughout the monitoring period. However, when we look at the extent of exceedance we can see that at no point does pH exceed 8.5. Therefore, the lack of significance with AWQI is probably reflective of the small deviations in pH values between 1992 and 2003.

For AWQI we observed similarities between Warsaw and Kiezmark in that iron, ammonia and chloride were driving the index value. Chloride values, compared to those observed at Kiezmark, were one order of magnitude lower in Warsaw, which supports the previous theory of a natural salinity gradient: increasing dissolved salts with distance from headwaters. However, the high chloride content may also be a reflection of point source pollution from the coal mines further upstream (Kowalkowski *et al.*, 2007), or a combination of both. The drop in iron and the decrease in ammonia after 1996 seemed to be the major influence resulting in an increase in AWQI. Again, the ammonia results are reflective of previous investigations conducted in the Vistula River that report sewage contamination (Buszewski and Kowalkowski, 2003). The result is also reflective of the fact that the monitoring station is situated within the major city of Warsaw and is simply an indication of urban point source pollution.

For HWQI, we observed a very similar pattern with Kiezmark in that the predominant parameters to exceed the guideline were metals, specifically cadmium, lead, manganese and mercury. Unfortunately, because mercury was not measured after 1995 at this station we were unable to assess the trend over the full monitoring period. However, up until 1995 the trend of mercury was similar to the other metals, as it was decreasing in concentration. This decrease in metals over the monitoring period resulted in a corresponding increase in the HWQI. These results are also reflective of investigations concluding that the Vistula River is a major source of metal contamination in the bay of Gdansk (Pempkowiak *et al.*, 2006; Beldowski and Pempkowiak, 2007).

When the two indices are combined to form the DWQI, again we observe exactly the same parameters indicating this index is reflective of both HWQI and AWQI. From these observations we would conclude that the indices at Warsaw show a similar pattern to those at Kiezmark: metals are driving the HWQI, and, chloride and ammonia are driving the AWQI. In addition, chloride is one order of magnitude lower than the concentration observed at Kiezmark, this observation supports the theory of a salinity gradient from upstream to downstream.

3) Kraków – Station 021003

The parameters that exceeded the guideline at Kraków are illustrated in Figure 21. The annual averages of these parameters were then plotted against their respective guideline for each index (Figures 22 to 24) and correlation analysis conducted. The results of this analysis are reported in Table 15.

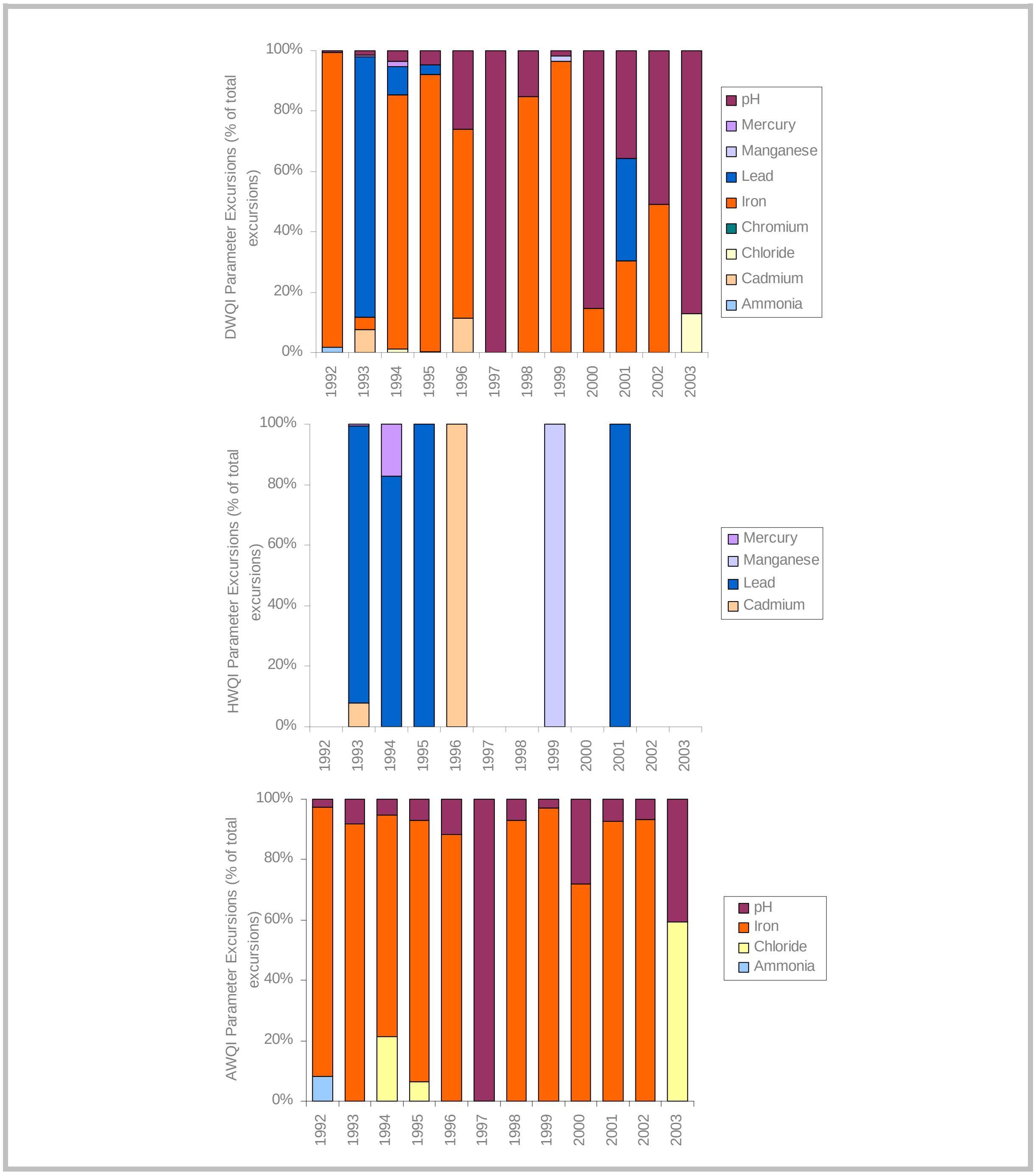

Figure 21: Parameter excursions for Kraków (Station 021003), as a percentage of total excursions per annum, for DWQI, HWQI and AWQI.

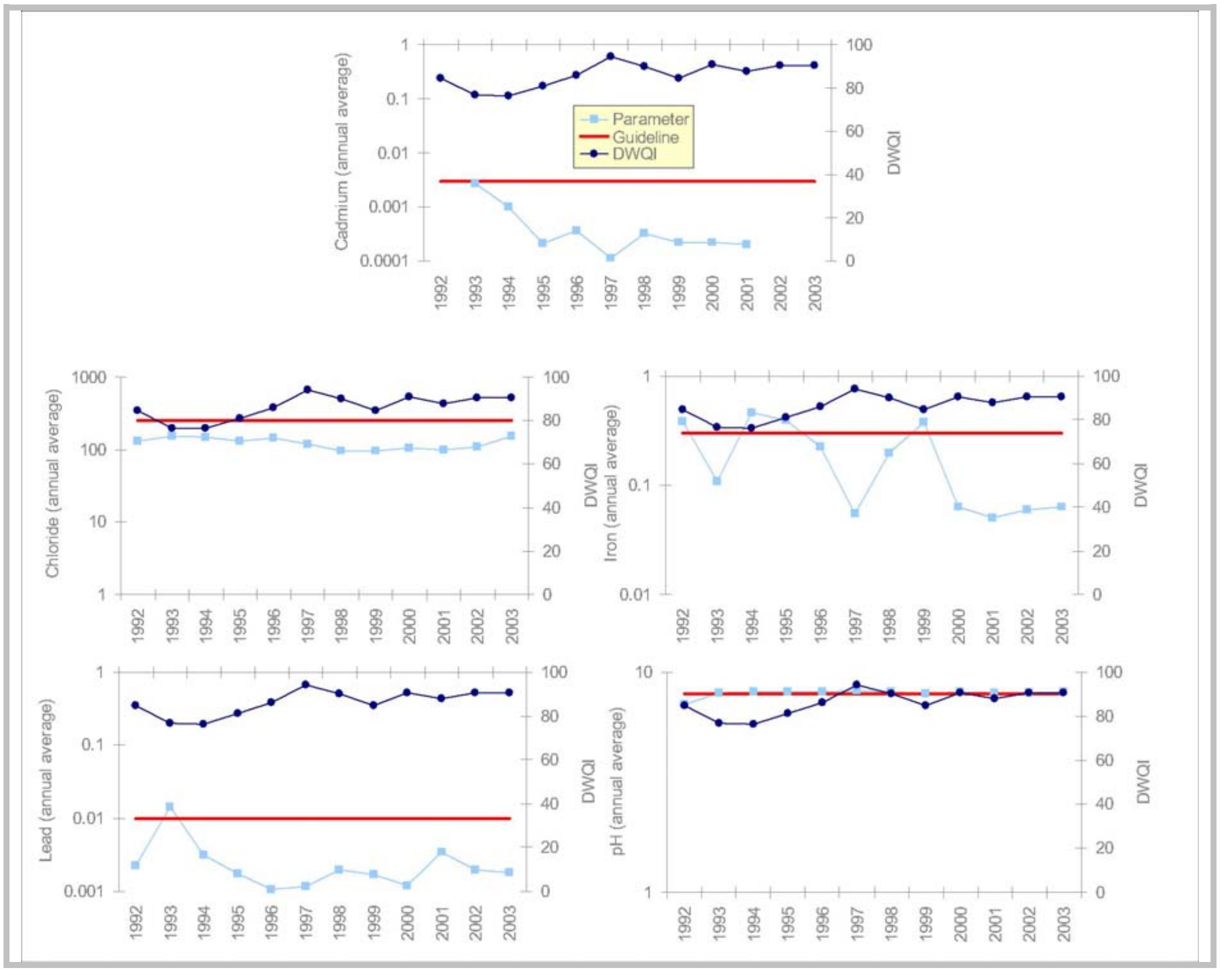

Figure 22: Annual averages of each parameter, their respective guideline and associated DWQI for Kraków Station 021003 from 1992 to 2003.

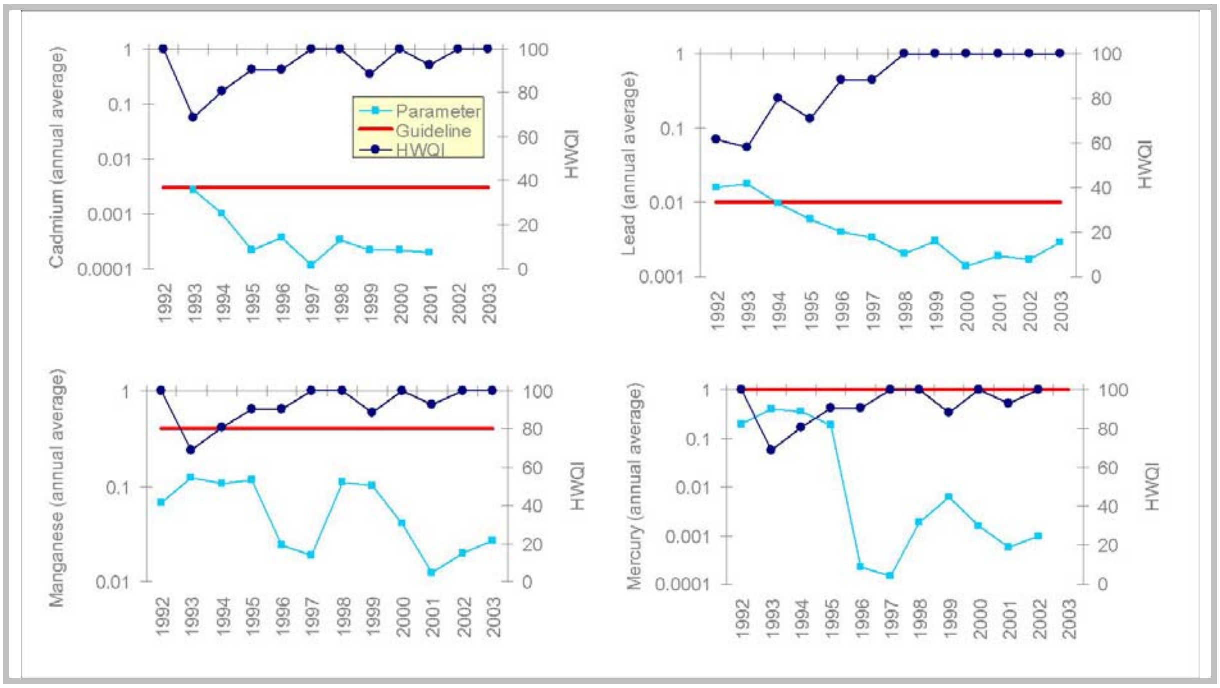

Figure 23: Annual averages of each parameter, their respective guideline and associated HWQI for Kraków Station 021003 from 1992 to 2003.

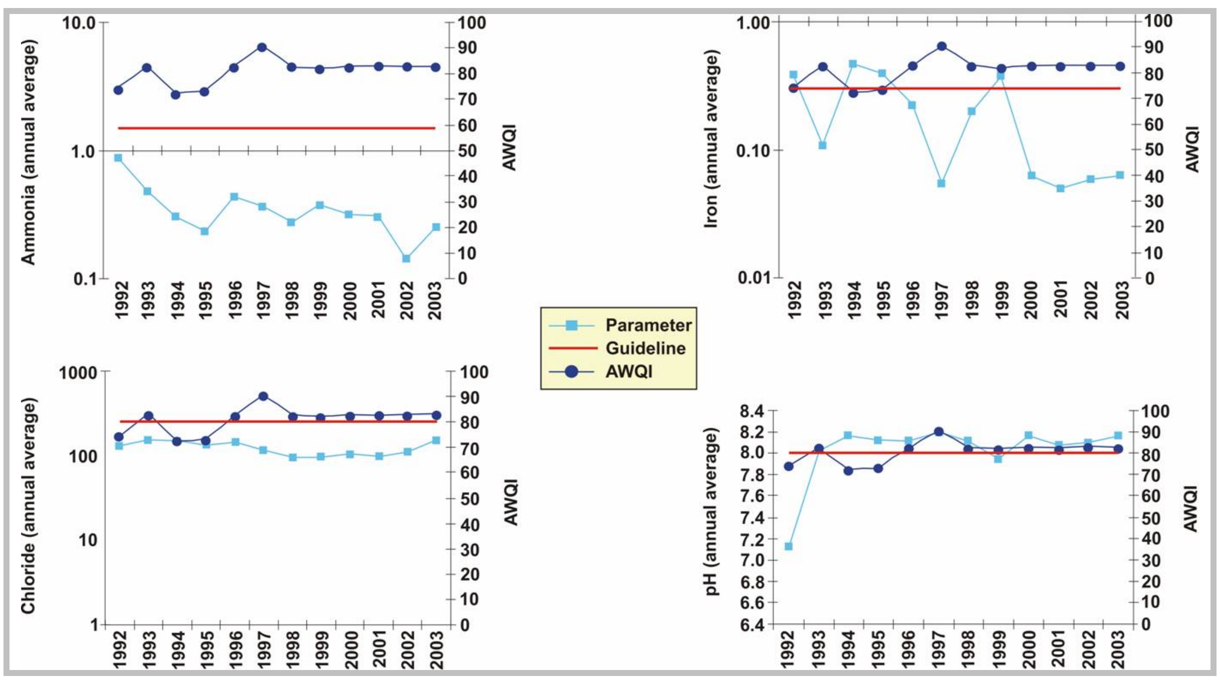

Figure 24: Annual averages of each parameter, their respective guideline and associated AWQI for Kraków Station 021003 from 1992 to 2003.

Table 15: Pearsons correlation matrix for DWQI, HWQI and AWQI against the contributing parameters at Kraków (Station 021003)

	DWQI	HWQI	AWQI
Ammonia			-0.146
Chloride	-0.533		-0.332
Cadmium	-0.691*	-0.883**	
Iron	-0.648		-0.754*
Lead	-0.589	-0.800**	
Manganese	-0.422	-0.590	
Mercury		-0.763**	
pH	-0.157		-0.400

Note: *Asterisks represent significant correlation in which::*
** = p<0.05, ** =p<0.01 and *** = p<0.001.*

Cadmium, lead and mercury were all significantly correlated with the HWQI (r= -0.863, p<0.01; r = -0.800, p<0.01; and r = -0.763, p<0.01 respectively). AWQI did not show such a strong correlation to all of the contributing parameters as in the previous sites i.e. only iron was significantly correlated (r=-0.754, p<0.05). Interestingly, only cadmium (r=-0.691, p<0.05) was significantly correlated with DWQI. (r = -0.754).

In HWQI, cadmium, lead and mercury are all significantly correlated which is a similar observation to the previous two sites, and, reflective of other investigations that identify the Vistula river as a significant source of metal contamination (Pempkowiak *et al.*, 2006; Beldowski and Pempkowiak, 2007). Although it is beyond the scope of this report to investigate the possible source of metal contamination in the Vistula River, the high concentrations of these metals may possibly be derived from the coal mines in the upstream areas of the river, as well as the zinc and lead mines in the Przemsza River, a main tributary to the Vistula River upstream of Kraków (Gueguen and Dominik, 2003). When we compare the concentrations of metals at this site to previously recorded concentrations at the same site, we observe similarities between cadmium, chromium, lead and zinc (Table 16). This would suggest that the concentrations observed in our database, and hence, reflected in our HWQI, are in agreement with previous studies conducted to observe the impacts of the mines in the upper reaches of the Vistula River.

Table 16: Comparison of concentrations in cadmium, chromium, lead and zinc (µg L^{-1}) at Krakow in 1998 between data recorded in GEMStat and data recorded by Guegen and Dominite (2003)

Metals (µg L^{-1} – filtered)	GEMStat	Gueguen and Dominite, 2003
Cadmium	0.2-0.6	0.7
Chromium	1.0-5.0	2.1
Lead	1.0-4.0	0.3
Zinc	2.0-57	99

In AWQI, iron was the only significant parameter to be correlated with the index. This corresponds with the previous two stations. The lack of significant correlation with chloride also supports the theory of a salinity gradient, indicating that dissolved salts were lower in the upstream site and increased in concentration towards the downstream site.

When the two indices are combined, it is interesting to note that only cadmium was significantly correlated with the DWQI. It would seem that when the indices are combined at this site, the correlation with parameters is lost. This is a concern, especially if we were only relying on the DWQI to accurately reflect the status of water quality in the Vistula River. HWQI and AWQI, it seems, were more sensitive than the DWQI, to pick up on the slight deviations in the parameters reported at this site, i.e. the exceedances above the guidelines were less severe at Kraków compared to the mid and downstream sites where DWQI accurately represented the HWQI and AWQI results. Hence, the HWQI and AWQI were more reflective of the situation within the Vistula River at this site. This result justifies are decision to split the indices into two.

Conclusions from the Case Studies

First, the significant correlations between the parameters in exceedance and the indices related well to previous studies conducted within the Vistula River, with high metal content reflected in the HWQI, and high chloride and ammonia content reflected in the AWQI. Most importantly, the parameters correlated well with their respective indices, suggesting that both HWQI and AWQI were truly reflective of the different parameters included within their calculation. On the whole, the indices were a good reflection of water quality in the Vistula River. The DWQI, while corresponding well to the other two since it demonstrated similar temporal and spatial patterns, did not seem to be as sensitive or as descriptive as the HWQI or AWQI. This is especially true for the upstream site at Kraków, where the correlations of the DWQI to the respective parameters were lower (Table 15). The HWQI and AWQI were more reflective of the exceeded parameters. This highlights the importance of the different indices. The DWQI can provide a very broad overview of the situation, but HWQI and AWQI are far more sensitive to deviations from the guideline and more descriptive in specific issues of concern. This is not to say that the DWQI is not useful, but rather that the decision to use either indice is dependent on the type of question or analysis that is being conducted.

One of the most interesting observations was that the gradients in different parameters from upstream to downstream. Specifically, certain metals, namely cadmium, chromium, lead and mercury increased in concentration from upstream to downstream with a corresponding decrease in HWQI. Ammonia and chloride also demonstrated an increase from upstream to downstream with a corresponding decrease in AWQI. To illustrate this relationship more clearly, these results are plotted in Figure 25.

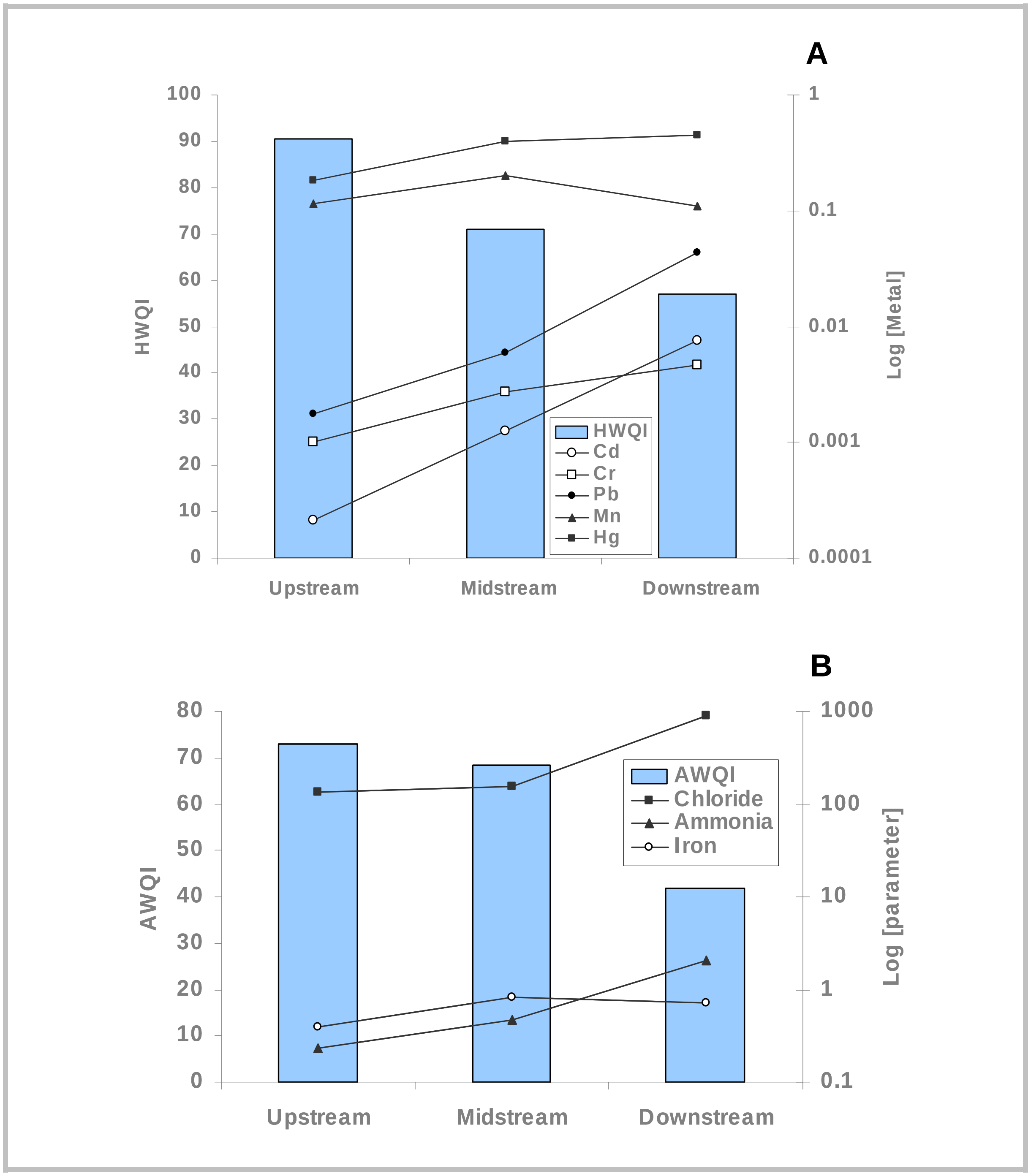

Figure 25: Spatial trends from upstream to downstream in A) HWQI and B) AWQI with corresponding parameter concentrations.

Therefore, not only were these indices reflective of the real data on a temporal basis, but also we are able to plot them on a spatial scale from upstream to downstream with meaningful results. We would conclude that this case study has demonstrated the usefulness and sensitivity of the indices developed and we would recommend them for further development and application.

Chapter 6 Future Developments

The objective of this report was to develop an index to assess drinking water quality using established guidelines and global data held by GEMStat. Although a significant effort has been made in the development of the indices, there are a number of issues that need to be addressed for their future development.

Firstly, the removal of faecal coliform bacteria (FCB) was required in the initial development stage because of its influence over the final index value in DWQI and HWQI. As a result, the current analysis does not include any measurement of microbial data, which is an important aspect in analysing the safety of drinking water. Its removal was based on two key issues: 1) the extent to which the parameter could deviate from the guideline; and 2) the uncertainty over the relevance of the current guideline. Other composite indices of water quality, reviewed earlier, do not require a benchmark or guideline comparison. For example, Pesce and Wunderlin (2000) normalized their data to a common scale, Stambuk-Giljanovik (2003) calculated a weighted average index from normalized values, and, Tsegaye *et al*. (2006) standardized values to the maximum concentration for each parameter. Application of these models to the current dataset would require the FCB values to be standardised, thereby controlling the extent of excursion from the guideline. It is therefore recommended that a comparative study be conducted with different models to assess both the consistency between the indices at a station, regional and global level, and the relative influence of FCB using the different models. It is also suggested that the development of a microbial WQI be conducted to run alongside HWQI. This way it will then be possible to assess whether 1) the weighted indices with FCB is still dominating the final index value compared to the current HWQI; and 2) the weighted indices is reflective of the microbial WQI.

By developing a separate microbial WQI and a weighted HWQI with FCB included, we can assess whether a further separate index is necessary, or whether a simple weighting calculation within the current index will overcome the issues observed in this report.

Secondly, a useful tool would be to prioritize pollutants to establish a framework for development of a DWQI, HWQI or AWQI for individual countries. As it stands, the selection of parameters in our indices are based on availability and appropriate geographical representation. They are certainly not all encompassing of the parameters outlined by the WHO in their guidelines for drinking water. As such, certain priority pollutants may have been missed, such as in areas of intense agriculture, the inclusion of certain pesticides would be essential. The long term goal of developing this tool would be to provide, on a local scale, guidance as to which parameters need to be measured to monitor water quality for drinking, and, how to use those data to monitor the situation through index development.

In addition, it is also important to note that the WHO guidelines used in this study are specifically for drinking water, and as such do not represent guidelines for source water. The data in GEMStat are predominantly assessing source water, and therefore, there are limitations in the parameters chosen. We are only selecting parameters that are considered to have a human health or acceptability issue in water with no further treatment required. Parameters such as BOD or DO are not recognised parameters affecting drinking water. However, these parameters may cause considerable problems if that water body is intended as a source to be treated for drinking since increased aeration or biological treatment of the water may be required to establish its suitability for drinking. The use of the WHO guidelines for drinking water is useful for assessing water quality against stringent guidelines and will be useful as an assessment tool for situations in which the water body is used as drinking water, with little or no treatment. It is recommended, however, that further development of the guideline include parameters that will affect the quality of water as a source for drinking. This will also provide an opportunity to assess the treatment level categories proposed in this report by gaining expert opinion regarding the relevance of the categories to their corresponding index values.

Thirdly, the development of the indices in this report included data from rivers, lakes and groundwater. Further development and assessment on a global scale will require separation of these data into types of water body being analysed. This will be a useful exercise to assess the difference in water quality between these three types of water bodies.

Finally, further assessment of indices will also be required to assess how well they reflect real data when there is not such a comprehensive data set as that observed in the Vistula River. Sensitivity analysis and validation of the indices, at sites lacking comprehensive data, is suggested to assess the strength of the index to reflect real data.

Overall, the three indices developed were reflective of the real data obtained from GEMStat, allowing assessment of water quality on both on a temporal and spatial scale. Further development of the index is now in progress.

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