# Water Quality

## For Ecosystem and Human Health

**United Nations Environment Programme**
**GEMS/Water Programme**

GLOBAL ENVIRONMENT MONITORING SYSTEM

Water Quality for Ecosystem and Human Health
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# Contents

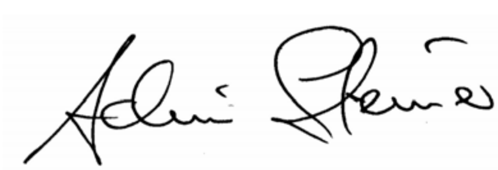
## Forward

Freshwater scarcity ranks among the most urgent environmental challenges of this century. To improve water management and measure the achievement of internationally agreed goals on water and sanitation, countries and organizations need access to relevant information.

The data and analyses presented in *Water Quality for Ecosystem and Human Health* are from GEMStat, the global water quality database created by UNEP's GEMS/Water Programme, the only programme in the UN system exclusively dedicated to monitoring and assessing environmental water quality. Drawing on examples from around the world, *Water Quality for Ecosystem and Human Health* presents assessments of current water quality status and trends. It also provides an introduction to a diverse range of global water quality issues, including approaches to their identification, analysis and resolution.

The wide range of environmental pressures in different countries and regions, and the reality of limited resources available for monitoring, assessment and remediation, make it difficult to obtain a global picture of water quality. However, the publication highlights a number of salient issues. On the negative side, human activities are the principal cause of deteriorating quality of water resources, even in remote environments, and impaired aquatic ecosystems can negatively impact human health and socio-economic progress. It is clear that new threats to aquatic ecosystems, for example by pharmaceuticals and personal care products, require immediate attention by regulatory authorities at all levels. On the positive side, successful procedures have been developed for restoring aquatic ecosystems, including remedying damage caused by acidification and eutrophication.

To build on these achievements and track the effectiveness of policies and interventions, both baseline data and long-term monitoring of aquatic ecosystems are a priority. The GEMS/Water Programme provides a vital contribution to monitoring progress towards meeting the Millennium Development Goal and World Summit on Sustainable Development targets on water and sanitation. Current pH data and assessment demonstrate that such targets can be met. This is only one example, but it does show that, at least in some parts of the world, the quality of water resources is improving. As such, *Water Quality for Ecosystem and Human Health* provides encouragement to continue, and increase, our efforts to protect and improve our water resources for ecosystem health and human well-being.



Achim Steiner
Executive Director, United Nations Environment Programme

## Preface

This is the first report of its kind produced by the GEMS/Water Programme, and the target audience includes academia, research scientists, and water practitioners. I hope that the report proves particularly useful and encouraging for my colleagues and their constituents in developing and transitional countries.

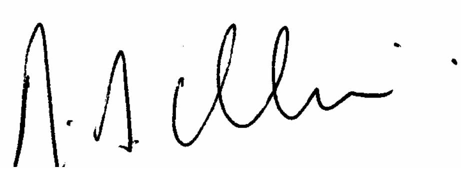
As Achim Steiner points out, measuring the achievement of the internationally agreed goals on water and sanitation is a core service provided by GEMS/Water, and emphasizes the importance of implementing UNEP's Bali Strategic Plan on Technology Transfer and Capacity Building, to improve data acquisition and quality, particularly in developing countries.

The difficulties involved in monitoring, describing and managing inland aquatic resources are not insurmountable, and certainly there are many examples of successful interventions. Here are a few from Asia:

- Concerns over health effects of certain compounds in humans and animals have lead to bans of certain pesticides in different parts of the world. Pesticide bans have brought in noticeable improvements in water quality for several rivers in China;
- Restoration of the marshes in Iraq is underway and early results show promising improvements in water quality and biodiversity; and
- River and lake restoration in Japan is extensive and many successes have been documented in systems that are heavily urbanized and located in areas of extremely high population densities.

Although many challenges remain to properly protect aquatic ecosystem health, there is proof that success can be reached with planning, political and institutional will, and financial and technical resources. The future of water quality at local, regional, and global scales depends on investments of individuals, communities, and governments at all political levels to ensure that water resources are protected and managed in a sustainable manner, and that our good health is the result.

I trust that readers will find this book to be interesting and useful, and I welcome your comments and feedback.



Richard Robarts,
Director, UNEP GEMS/Water Programme

# Chapter 1: Introduction

Water is vital to the existence of all living organisms, but this valued resource is increasingly being threatened as human populations grow and demand more water of high quality for domestic purposes and economic activities. Water abstraction for domestic use, agricultural production, mining, industrial production, power generation, and forestry practices can lead to deterioration in water quality and quantity that impact not only the aquatic ecosystem (i.e., the assemblage of organisms living and interacting together within an aquatic environment), but also the availability of safe water for human consumption. It is now generally accepted that aquatic environments cannot be perceived simply as holding tanks that supply water for human activities. Rather, these environments are complex matrices that require careful use to ensure sustainable ecosystem functioning well into the future. Moreover, the management of aquatic environments requires an understanding of the important linkages between ecosystem properties and the way in which human activities can alter the interplay between the physical, chemical and biological processes that drive ecosystem functioning.

Providing safe and secure water to people around the world, and promoting sustainable use of water resources are fundamental objectives of the Millennium Development Goals (Box 1). The international community has recognized the important links between ecosystem and human health and well-being, particularly as human populations expand and place ever greater pressures on natural environments. However, the ability to properly track progress toward minimizing impacts on natural environments and improving access of humans to safe water depends on the availability of data that document trends in both space and time. As such, ongoing monitoring of both water quality and quantity in surface and ground water resources is a necessary activity at all governing levels: local, national, and international.

Water quality and quantity are intimately linked although not often measured simultaneously. Water quantity is often measured by means of remote hydrological monitoring stations which record water level, discharge, and velocity. Monitoring of water quantity can be undertaken, to a certain degree, with a minimal amount of human intervention, once a monitoring station has been set up. In contrast, water quality is usually determined by analysing samples of water collected by teams of personnel visiting monitoring stations at regular intervals. The costs associated with monitoring the many parameters that influence water quality, when compared to those associated with monitoring only a few water quantity variables, usually means that water quality monitoring is not undertaken as frequently as water quantity monitoring. However, the results of water quality monitoring are vital to being able to track both spatial and temporal trends in surface and ground waters.

**Box 1. Millennium Development Goals and Water Quality**

The United Nations General Assembly, at its Millennium meeting in 2000, established eight Millennium Development Goals (MDGs) with targets to be achieved by 2015, with the aim of speeding up poverty alleviation and socio-economic development. The MDGs were elaborated and endorsed by the intergovernmental community at the World Summit on Sustainable Development, convened in Johannesburg in 2002.

Millennium Development Goals:

Eradicate extreme hunger and poverty
Achieve universal primary education
Promote gender equality and empower women
Reduce child mortality
Improve maternal health
Combat HIV/AIDS, malaria and other diseases
Ensure environmental sustainability
Develop a global partnership for development.

Water quality management contributes both directly and indirectly to achieving the targets set out in all eight MDGs, although it is most closely tied to specific targets of the goal 7, to ensure environmental sustainability:

- Integrate the principles of sustainable development into country policies and programmes and reverse the loss of environmental resources;
- Halve by 2015 the proportion of people without sustainable access to safe drinking water and basic sanitation;
- Significantly reduce biodiversity loss by 2010; and
- Achieve significant improvements in the lives of at least 100 million slum dwellers, by 2020.

Indicators of water quality can be used to demonstrate progress toward the targets, by plotting trends in water quality over time and over space.

This document is intended to provide an overview of the major components of surface and ground water quality and how these relate to ecosystem and human health. Local, regional, and global assessments of water quality monitoring data are used to illustrate key features of aquatic environments, and to demonstrate how human activities on the landscape can influence water quality in both positive and negative ways. Clear and concise background knowledge on water quality can serve to support other water assessments.

## Defining Water Quality

The quality of any body of surface or ground water is a function of either or both natural influences and human activities. Without human influences, water quality would be determined by the weathering of bedrock minerals, by the atmospheric processes of evapotranspiration and the deposition of dust and salt by wind, by the natural leaching of organic matter and nutrients from soil, by hydrological factors that lead to runoff, and by biological processes within the aquatic environment that can alter the physical and chemical composition of water. As a result, water in the natural environment contains many dissolved substances and non-dissolved particulate matter. Dissolved salts and minerals are necessary components of good quality water as they help maintain the health and vitality of the organisms that rely on this ecosystem service (Stark *et al*., 2000). Figure 1 shows the distribution of water hardness, a water quality parameter that is most influenced by the geology of the surrounding drainage basin, in lake and river monitoring stations worldwide.

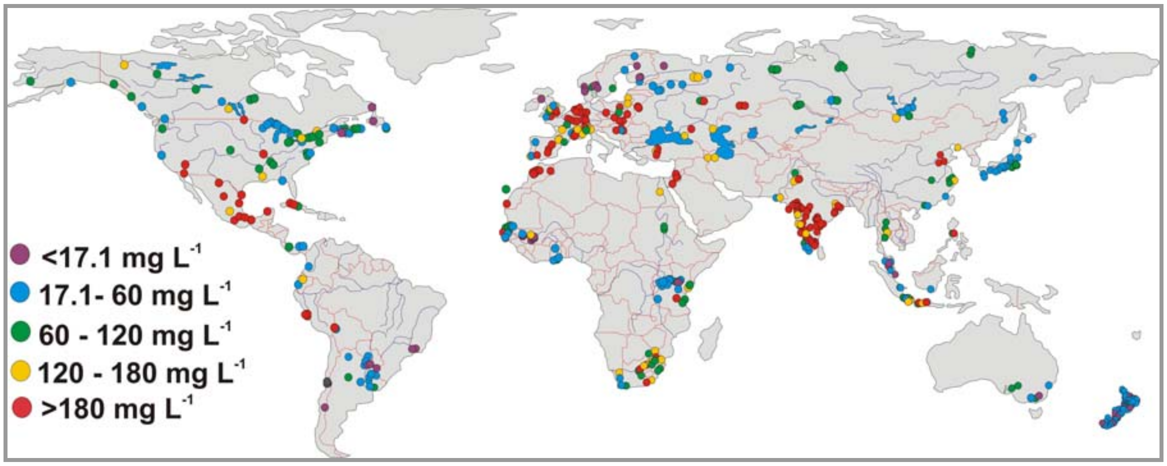



Figure 1. Water hardness (mg $L^{-1}$) at surface water monitoring stations.

Water can also contain substances that are harmful to life. These include metals such as mercury, lead and cadmium, pesticides, organic toxins and radioactive contaminants. Water from natural sources almost always contains living organisms that are integral components of the biogeochemical cycles in aquatic ecosystems. However, some of these, particularly bacteria, protists, parasitic worms, fungi, and viruses, can be harmful to humans if present in water used for drinking.

The availability of water and its physical, chemical, and biological composition affect the ability of aquatic environments to sustain healthy ecosystems: as water quality and quantity are eroded, organisms suffer and ecosystem services may be lost. Moreover, an abundant supply of clean, usable water is a basic requirement for many of the fundamental uses of water on which humans depend. These include, but are not limited to:

- water used for human consumption and public water supply;
- water used in agriculture and aquaculture;
- water used in industry;
- water used for recreation; and
- water used for electrical power generation.

The quality of water necessary for each human use varies, as do the criteria used to assess water quality. For example, the highest standards of purity are required for drinking water, whereas it is acceptable for water used in some industrial processes to be of less quality.

The quality of water required to maintain ecosystem health is largely a function of natural background conditions. Some aquatic ecosystems are able to resist large changes in water quality without any detectable effects on ecosystem composition and function, whereas other ecosystems are sensitive to small changes in the physical and chemical make up of a body of water and this can lead to degradation of ecosystem services and loss of biological diversity. The degradation of physical and chemical water quality due to human influences is often gradual, and subtle adaptations of aquatic ecosystems to these changes may not always be readily detected until a dramatic shift in ecosystem condition occurs. For example, in many shallow European lakes, the gradual enrichment of the surface water with plant nutrients has resulted in shifts from systems that once were dominated by rooted aquatic plants to systems that are now dominated by algae suspended in the water column (Scheffer *et al*. 2001). Regular monitoring of the biological, physical, and chemical components of aquatic ecosystems can serve to detect extreme situations in which the ability of an ecosystem to return to its normal state is stretched beyond its limit.

Typically, water quality is determined by comparing the physical and chemical characteristics of a water sample with water quality guidelines or standards. Drinking water quality guidelines and standards are designed to enable the provision of clean and safe water for human consumption, thereby protecting human health. These are usually based on scientifically assessed acceptable levels of toxicity to either humans or aquatic organisms. Annex 1 provides a summary of international and national guidelines and standards for drinking water quality. Guidelines for the protection of aquatic life are more difficult to set, largely because aquatic ecosystems vary enormously in their composition both spatially and temporally, and because ecosystem boundaries rarely coincide with territorial ones. Therefore, there is a movement among the scientific and regulatory research community to identify natural background conditions for chemicals that are not toxic to humans or animals and to use these as guidelines for the protection of aquatic life (Robertson *et al*., 2006; Dodds and Oakes, 2004; Wickham *et al*., 2005). Other guidelines, such as those designed to ensure adequate quality for recreational, agricultural or industrial activities, set out limits for the physical, chemical, and biological composition of water needed to safely undertake different activities.

# Chapter 2: Measuring Water Quality

Water quality is neither a static condition of a system, nor can it be defined by the measurement of only one parameter. Rather, it is variable in both time and space and requires routine monitoring to detect spatial patterns and changes over time. There is a range of chemical, physical, and biological components that affect water quality and hundreds of variables could be examined and measured. Some variables provide a general indication of water pollution, whereas others enable the direct tracking of pollution sources.

The UNEP GEMS/Water Programme maintains an extensive global database of chemical, physical and biological water quality parameters commonly measured in surface and ground water monitoring programmes (Table 1). Although not exhaustive, the suite of parameters measured and discussed in this book provides the information required to evaluate the state of an aquatic ecosystem according to ecosystem requirements and human uses. Unless otherwise noted, data used to generate figures throughout this document are from the GEMS/Water global water quality online database, GEMStat.

Table 1. Number of stations and of observations of water quality parameters separated by class and geographic region contained in GEMStat (August 1, 2006).

| Region | No. Stations | Physical/ Chemical | Nutrients | Major Ions | Metals | Organic Matter | Organic Cont-aminants | Micro-biology | Hydrologic al & Sampling Variables | Date Range |
|---|---|---|---|---|---|---|---|---|---|---|
| Africa | 176 | 45529 | 39504 | 75152 | 6580 | 1757 | 556 | 1107 | 193 | 1977-2005 |
| Americas | 1824 | 79405 | 57867 | 68297 | 92214 | 7316 | 4548 | 11771 | 7641 | 1965-2004 |
| Asia | 329 | 206742 | 110237 | 141029 | 90909 | 45334 | 10030 | 36864 | 13612 | 1971-2006 |
| Europe | 316 | 226260 | 131702 | 129594 | 164289 | 64349 | 20513 | 35846 | 64521 | 1978-2004 |
| Oceania | 94 | 189178 | 80327 | 11026 | 2986 | 14134 | 1438 | 1649 | 31020 | 1979-2004 |
| Total | 2743 | 747114 | 419637 | 425098 | 356978 | 132890 | 37085 | 87237 | 116987 | 1965-2006 |

The GEMStat data have been collected from the GEMS/Water Global Network which includes over 2,700 baseline, trend and flux stations. As described in Box 2, there are three types of monitoring stations in the GEMS/Water global monitoring network "baseline," "trend" and "flux" stations. (UNEP GEMS/Water Programme, 2005.)

**Box 2. Types of Stations**

Baseline Stations are typically located in headwater lakes, undisturbed upstream river stretches, and in aquifers where no known direct diffuse or point-sources of pollutants are likely to be found. They are used to establish natural water quality conditions; to provide a basis for comparison with trend and flux stations; and to determine, through trend analysis, the influence of long-range transport of contaminants and of climatic changes.

Trend Stations are typically located in major river basins, lakes or aquifers. They are used to track long-term changes in water quality related to pollution sources and land uses; to provide a basis for identifying causes or influences on measured conditions or identified trends. Since trend stations are intended to capture human impacts on water quality, the number of trend stations is relatively higher than the other types of stations, to cover the variety of water quality issues facing various basins. Most trend stations are located in basins with a range of pollution-inducing activities. However, some stations can be located in basins with single, dominant activities. Some trend stations may also serve as global river flux stations.

Flux Stations are located at the mouth of rivers as they exit to the coast. They are used to determine integrated annual fluxes of pollutants from river basins to oceans or regional seas, thereby contributing to geochemical cycles. For calculating chemical fluxes, water flow measurements must be obtained at the location of the global river flux stations.

## *Physical and Chemical Characteristics of a Water Body*

### Temperature

Temperature affects the speed of chemical reactions, the rate at which algae and aquatic plants photosynthesize, the metabolic rate of other organisms, as well as how pollutants, parasites, and other pathogens interact with aquatic residents. Temperature is important in aquatic systems because it can cause mortality and it can influence the solubility of dissolved oxygen (DO) and other materials in the water column (e.g., ammonia). Water temperatures fluctuate naturally both daily and seasonally. The maximum daily temperature is usually several hours after noon and the minimum is around daybreak. Water temperature varies seasonally with air temperature.

Vertical gradients in temperature can often be measured in deeper systems, especially in lakes where thermal stratification is common, such as those shown for Lake Ontario, Canada, in Figure 2. A warm upper layer, called the epilimnion, often develops during summer months in temperate regions, while a cool bottom layer, the hypolimnion, can be detected below the thermocline. Temperature gradients are set up due to the physical properties of water, where water is most dense at 4ºC, ensuring that cooler waters will typically be found at the bottom of lakes and deep rivers. Exceptions to this pattern can be found in ice covered systems, where an inverse temperature gradient may be set up and the upper layer of water is cooler than the bottom layer.

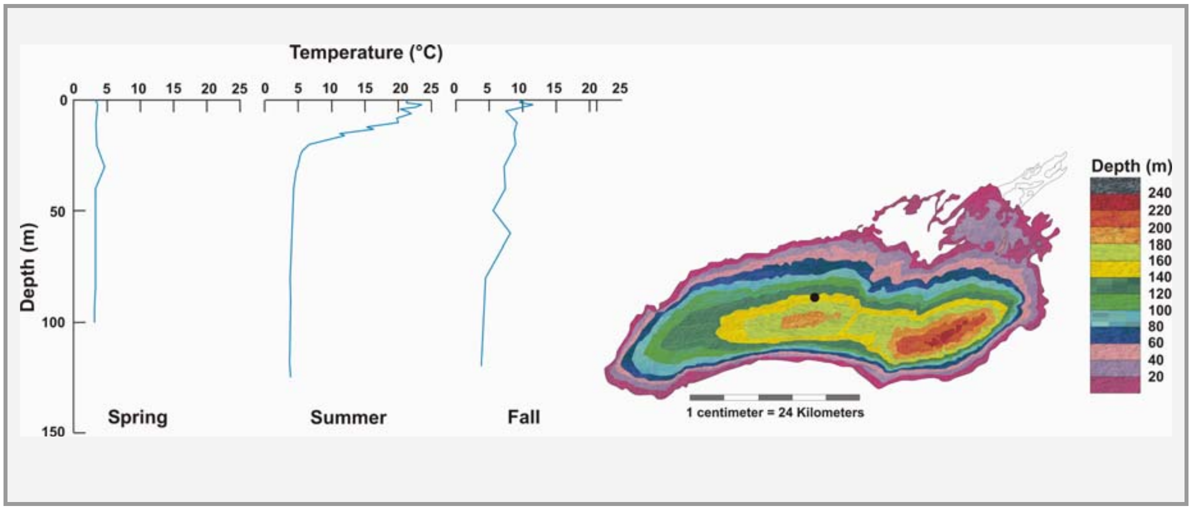



Figure 2. Seasonal patterns in depth profiles of temperature in Lake Ontario, Canada, with data from 1993. Note the approximately uniform and cool temperatures in spring (May), the strong thermocline between approximately 10 and 25m depth during the summer months (June – September), and the breakdown of the thermocline in the fall months to cooler and more uniform temperatures (October).

Aquatic organisms often have narrow temperature tolerances. Thus, although water bodies have the ability to buffer against atmospheric temperature extremes, even moderate changes in water temperatures can have serious impacts on aquatic life, including bacteria, algae, invertebrates and fish. Thermal pollution comes in the form of direct impacts, such as the discharge of industrial cooling water into aquatic receiving bodies, or indirectly through human activities such as the removal of shading stream bank vegetation or the construction of impoundments.

## Dissolved Oxygen

Oxygen that is dissolved in the water column is one of the most important components of aquatic systems. Oxygen is required for the metabolism of aerobic organisms, and it influences inorganic chemical reactions. Oxygen is often used as an indicator of water quality, such that high concentrations of oxygen usually indicate good water quality. Oxygen enters water through diffusion across the water's surface, by rapid movement such as waterfalls or riffles in streams (aeration), or as a by-product of photosynthesis. The amount of dissolved oxygen gas depends highly on temperature and somewhat on atmospheric pressure. Salinity also influences dissolved oxygen concentrations, such that oxygen is low in highly saline waters and vice versa. The amount of any gas, including oxygen, dissolved in water is inversely proportional to the temperature of the water; as temperature increases, the amount of dissolved oxygen (gas) decreases. This pattern is depicted for an annual cycle in the Murray River, Australia, in Figure 3.

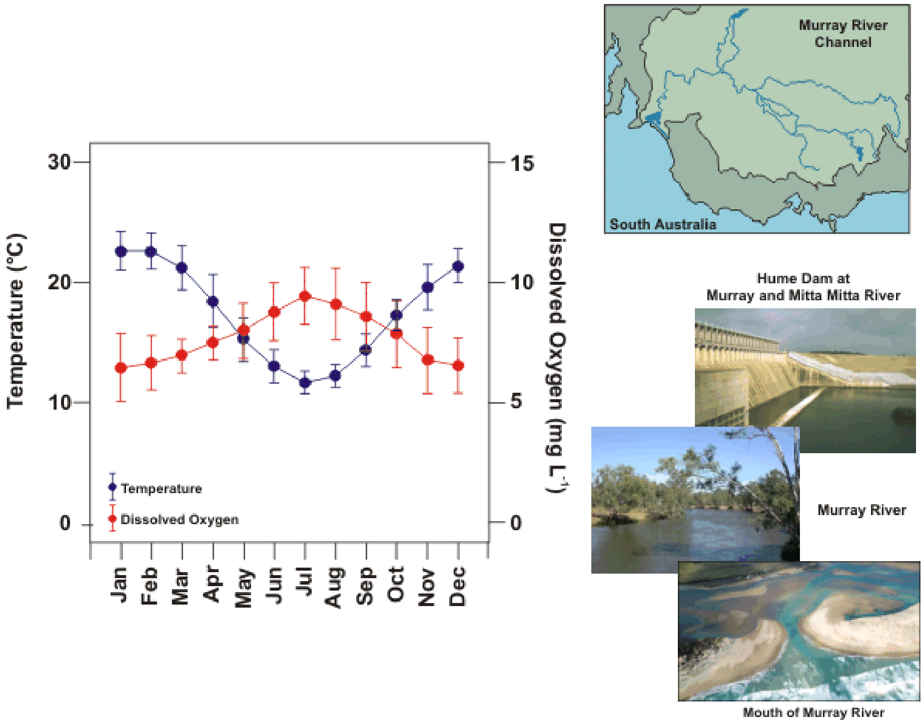



Figure 3. Seasonal patterns in dissolved oxygen and temperature in the Murray River, Australia. Data are monthly means ± 1 standard deviation. Note that peaks in water temperature coincide with dissolved oxygen minima over the course of a year.

Many productive lakes experience periods of oxygen depression or depletion in deep waters during warm summer months when strong temperature gradients are established between the warm surface and cool deep water. High algal production in the surface waters can lead to depleted oxygen concentrations at depth as cells die and settle to the bottom of the lake, where they are decomposed by bacteria. The decomposition process consumes oxygen from the water through bacterial respiration. Localized depression of oxygen was detected in the past in Lake Baikal, Russia, but depressions were not as pronounced in recent years, probably due to improved water quality in the lake (Figure 4).

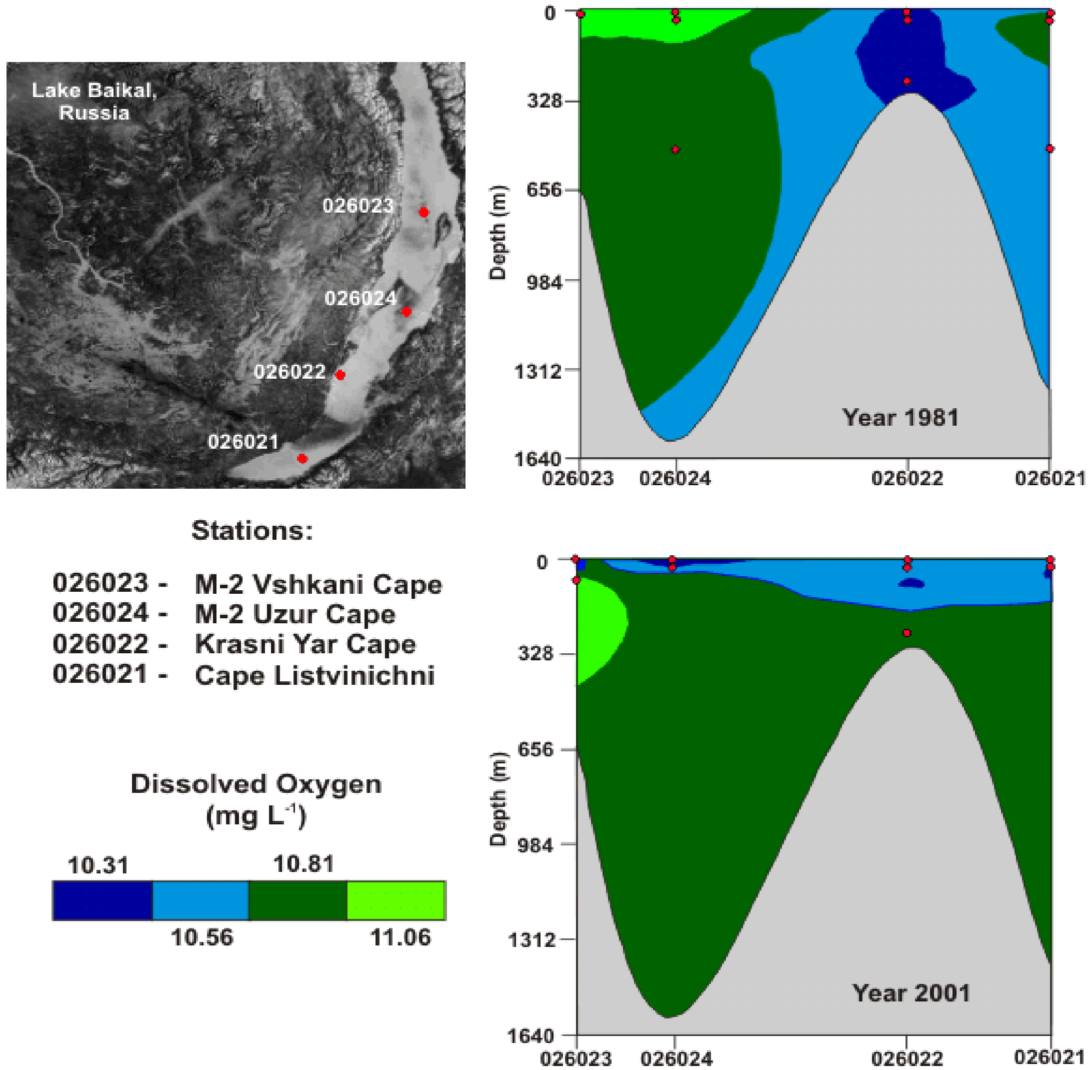



Figure 4. Localized oxygen depression in Lake Baikal, Russian Federation. Note that oxygen depression was more pronounced in Lake Baikal in the shallow basin around Krasni Yar Cape in the early 1980s compared to the early 2000s.

## pH and Alkalinity

In water, a small number of water ($H_2O$) molecules dissociate and form hydrogen ($H^+$) and hydroxyl ($OH^-$) ions. If the relative proportion of the hydrogen ions is greater than the hydroxyl ions, then the water is defined as being acidic. If the hydroxyl ions dominate, then the water is defined as being alkaline. The relative proportion of hydrogen and hydroxyl ions is measured on a negative logarithmic scale from 1 (acidic) to 14 (alkaline): 7 being neutral (US EPA, 1997; Friedl *et al*., 2004) (Figure 5).

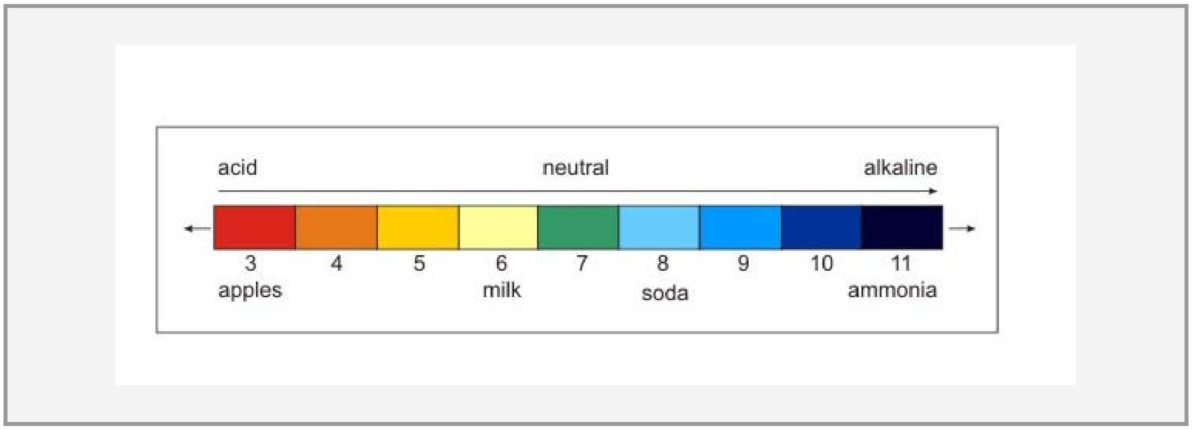



Figure 5. pH scale bar

The pH of an aquatic ecosystem is important because it is closely linked to biological productivity. Although the tolerance of individual species varies, pH values between 6.5 and 8.5 usually indicate good water quality and this range is typical of most major drainage basins of the world, as depicted in Figure 6. Natural acidity in rainwater is caused by the dissolution of atmospheric carbon dioxide ($CO_2$). The hydrogen ions entering a drainage basin in rainwater are neutralized by carbonate and silicate minerals as water percolates through soils. This neutralization capacity in soils determines whether or not acid precipitation will cause water quality impacts in receiving water bodies. The ability of rocks and soils in any given drainage basin to buffer the acidity of rainwater is related to the residence time of water in the soil as well as the levels of calcium carbonate, bicarbonate, and silicate minerals (Friedl *et al*., 2004; Wetzel and Likens, 2000).

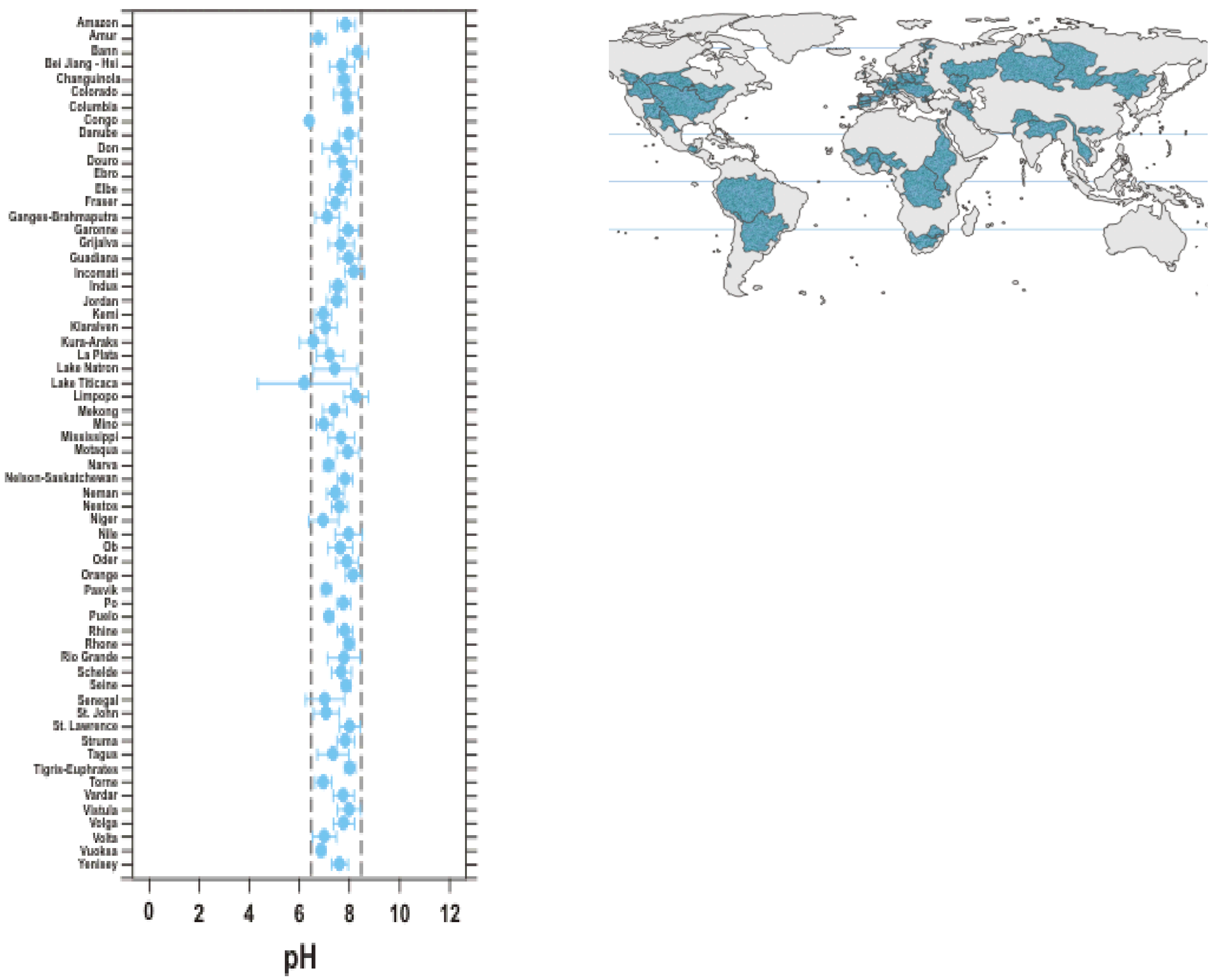
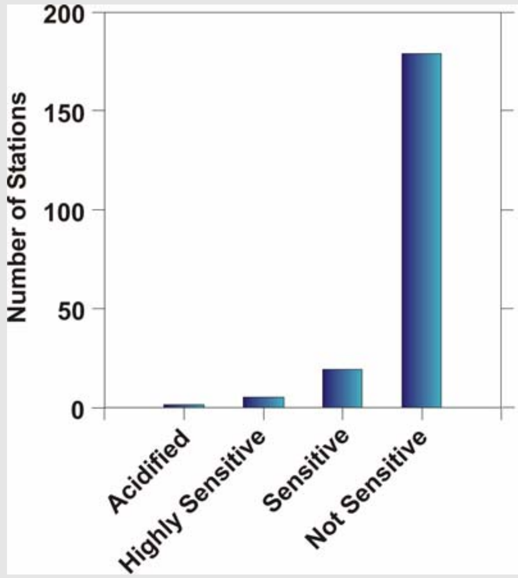



Figure 6. Mean pH (± 1 standard deviation) of major drainage basins in the world. Dashed lines indicate approximate pH range suitable for the protection of aquatic life.

Alkalinity is a related concept that is commonly used to indicate a system's capacity to buffer against acid impacts. Buffering capacity is the ability of a body of water to resist or dampen changes in pH. Alkaline compounds in water such as bicarbonates, carbonates, and hydroxides remove $H^+$ ions and lower the acidity of the water (i.e., increase pH). Out of a total of 204 monitoring stations examined worldwide, 88 percent had alkalinities that lead to classifications as being insensitive to acidification, whereas only three percent of stations were classified as being either highly sensitive or already acidified, as determined by classification schemes proposed by the Swedish Environmental Protection Agency (2002) and Godfrey *et al*. (1996) (Figure 7).




| Sensitivity Category | Buffering Capacity | Alkalinity (mg $CaCO_3$ $L^{-1}$) |
|---|---|---|
| Acidified | None | <1 |
| Critical | Very weak | <2 |
| Endangered | Weak | 2-5 |
| Highly sensitive | Good | 5-10 |
| Sensitive | Very good | 10-20 |
| Not sensitive | Very good | >20 |

Figure 7. Distribution of 204 surface water monitoring stations according to sensitivity to acidification.

Water that percolates through soil in poorly buffered catchments, usually those with hard igneous rocks, tends to be dominated by dissolved organic acids and can produce pH values in watercourses as low as 4.0. This is typical in areas downstream of peat bogs and other wetlands. These conditions can produce acidic 'blackwaters' that have very low water hardness and mineral content and low biological productivity. In contrast, catchments on sedimentary rock, especially calcareous rocks, which are rich in carbonates, have a high content of weatherable silicates, have high base saturation (long residency times), and are well buffered and generally give rise to circumneutral (pH 7) or slightly alkaline hard water streams (pH of 7.5 to 8.5).

## Turbidity and Suspended Solids

Turbidity refers to water clarity. The greater the amount of suspended solids in the water, the murkier it appears, and the higher the measured turbidity. The major source of turbidity in the open water zone of most lakes is typically phytoplankton, but closer to shore, particulates may also include clays and silts from shoreline erosion, re-suspended bottom sediments, and organic detritus from stream and/or water discharges. Suspended solids in streams are often the result of sediments carried by the water, as depicted by the relationship between discharge and suspended solids in the Yellow River, China (Figure 8). The source of these sediments includes natural and anthropogenic (human) activities in the watershed, such as natural or excessive soil erosion from agriculture, forestry or construction, urban runoff, industrial effluents, or excess phytoplankton growth (US

EPA, 1997). Turbidity is often expressed as total suspended solids (TSS). Water transparency and Secchi disk depth are also commonly-used measures of water quality that quantify the depth of light penetration in a body of water. Water bodies that have high transparency values typically have good water quality.

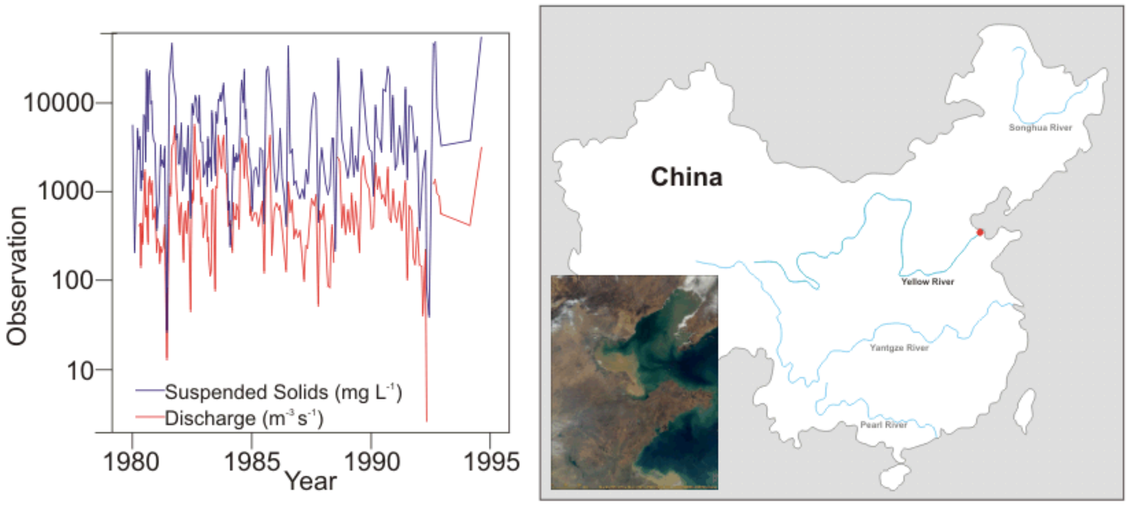



Figure 8. Suspended solids and instantaneous discharge measured in the Yellow River, China, at Lijin, approximately 80km from the mouth of the river. Note how closely suspended solids concentrations track instantaneous discharge over time.

## Salinity and Specific Conductance

Salinity is an indication of the concentration of dissolved salts in a body of water. The ions responsible for salinity include the major cations (calcium, $Ca^{2+}$; magnesium, $Mg^{2+}$; sodium, $Na^{+}$; and potassium, $K^{+}$) and the major anions (carbonates, $CO_3^{2-}$ and $HCO_3^{2-}$; sulphate, $SO_4^{2-}$; and chloride, $Cl^{-}$). The level of salinity in aquatic systems is important to aquatic plants and animals as species can survive only within certain salinity ranges (Friedl *et al*., 2004). Although some species are well-adapted to surviving in saline environments, growth and reproduction of many species can be hindered by increases in salinity.

Salinity is measured by comparing the dissolved solids in a water sample with a standardized solution. The dissolved solids can be estimated using total dissolved solids (see: turbidity) or by measuring the specific conductance. Specific conductance, or conductivity, measures how well the water conducts an electrical current, a property that is proportional to the concentration of ions in solution. Conductivity is often used as a surrogate of salinity measurements and is considerably higher in saline systems than in non-saline systems, as shown in Figure 9 (Dodds, 2002).

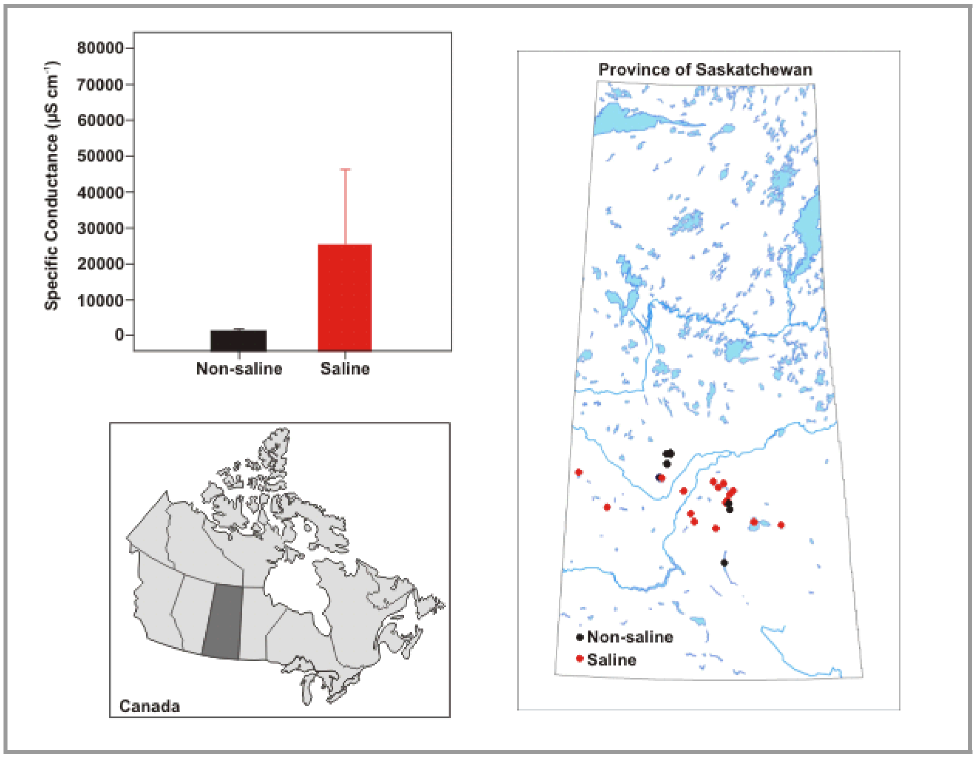



Figure 9. Specific conductance (µS $cm^{-1}$) of 17 saline and 9 non-saline lakes in Saskatchewan, Canada. Lakes with > 3.0 mg $L^{-1}$ total dissolved solids were classified as saline, following Hammer (1986). Data are mean ± 1 standard deviation. Data are from Arts *et al*. (2000).

Saline systems are by no means restricted to marine environments. In fact, saline inland waters often have salinities and conductivities that far exceed those of marine environments and can be found on all continents, including Antarctica. Saline lakes and ponds usually have no or little known outflow of water from the system beyond evaporation. Salts that are weathered from the surrounding drainage basin enter the lake through inflowing streams or during runoff events. Evaporation of water from the lake then leads to the concentration of salts within the system. Regions where evaporative losses of water exceed average precipitation, such as the northern Great Plains region of North America, tend to have many saline inland aquatic systems. The salinity and conductivity of a system will tend to change depending on the recharge of the system: during wet periods, salinity and conductivity will decline as the concentration of salts becomes more dilute, whereas dry periods will lead to increased salinity and conductivity values. These changes can occur over the course of a season, as shown in Figure 10, or over the course of many decades.

Municipal, agricultural, and industrial discharges can contribute ions to receiving waters or can contain substances that are poor conductors (organic compounds) changing the conductivity of the receiving waters. Thus, specific conductance can also be used to detect pollution sources (Stoddard *et al*., 1999).

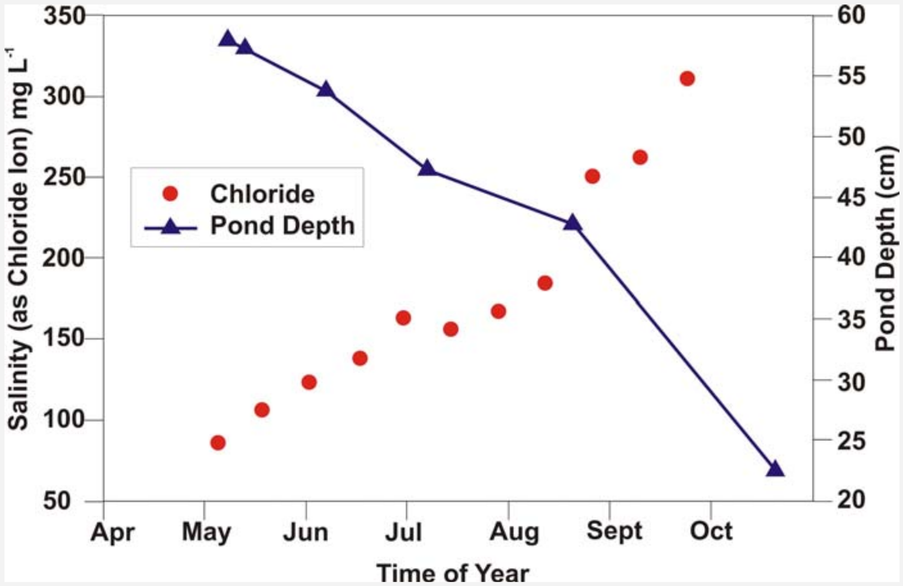



Figure 10. Relationship between salinity (measured as chloride concentration) and pond depth over the course of a growing season in a small, saline pond (Pond 50, St. Denis National Wildlife Refuge) in Saskatchewan, Canada. Data collected in 2000, M.J. Waiser, Environment Canada.

### *Major Ions*

The ionic composition of surface and ground waters is governed by exchanges with the underlying geology of the drainage basin and with atmospheric deposition. Human activities within the drainage basin also influence the ionic composition, by altering discharge regimes and transport of particulate matter across the landscape, and by changing the chemical composition of surface runoff and atmospheric deposition of solutes through wet and dry precipitation.

Global average concentrations of the four major cations (calcium, magnesium, sodium, and potassium) and the four major anions (bicarbonate, carbonate, sulphate, and chloride) in surface water tend to approach patterns in which calcium concentrations dominate the cations and bicarbonate and/or carbonate concentrations dominate the anions (Wetzel, 2001). However, as Table 2 shows, there is considerable variability in the patterns for cations in rivers on a global scale.

Table 2. Median composition of major cations in rivers and lakes around the world

| | Cations (mg L$^{-1}$) | | | |
|---|---|---|---|---|
| **Region** | **Calcium** | **Magnesium** | **Sodium** | **Potassium** |
| Africa | 13 | 5 | 18 | 4 |
| Americas | 22 | 6 | 8 | 1 |
| Asia | 20 | 9 | 11 | 2 |
| Europe | 45 | 6 | 10 | 2 |
| Oceania | 8 | 2 | 6 | 1 |

The ionic composition of surface waters is usually considered to be relatively stable and insensitive to biological processes occurring within a body of water. Magnesium, sodium and potassium concentrations tend not to be heavily influenced by metabolic activities of aquatic organisms, whereas calcium can exhibit marked seasonal and spatial dynamics as a result of biological activity. Similarly, chloride concentrations are not heavily influenced by biological activity, whereas sulphate and inorganic carbon (carbonate and bicarbonate) concentrations can be driven by production and respiration cycles of the aquatic biota (Wetzel, 2001). External forces such as climatic events that govern evaporation and discharge regimes and anthropogenic inputs can also drive patterns in ionic concentrations. Such forces are probably most responsible for long-term changes in the ionic composition of lakes and rivers. For example, long-term monitoring of the ionic composition of the Al Massira Reservoir in Morocco does not reveal any strong annual or seasonal cycles; changes in the chemical composition over time are more likely the result of external forces driving evaporation and discharge regimes (Figure 11).

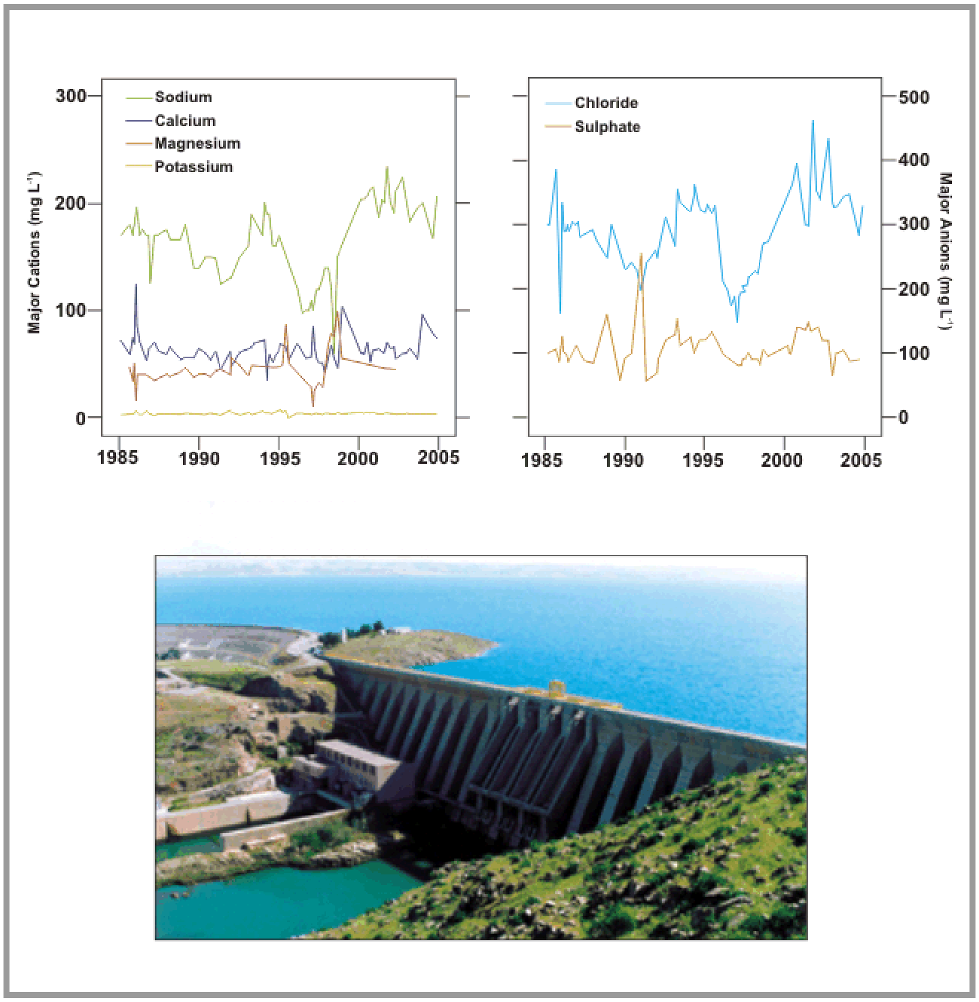



Figure 11. Concentrations of major cations (left panel) and anions (right panel) in the surface waters of Al Massira Reservoir, Morocco, between 1985 and 2005. Carbonate and bicarbonate concentrations were not measured over the sampling period. Note the similarity in temporal patterns of sodium and chloride concentrations.

## *Nutrients*

Nutrients are elements essential to life. The major nutrients, or macronutrients, required for metabolism and growth of organisms include carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, sulphur, magnesium, and calcium. In aquatic systems, nitrogen and phosphorus are the two nutrients that most commonly limit maximum biomass of algae and aquatic plants (primary producers), which occurs when concentrations in the surrounding environment are below requirements for optimal growth of algae, plants and bacteria. There are many micronutrients also required for metabolism and growth of organisms, but for the most part, cellular demands for these nutrients do not exceed supply. For example, elements such as iron (Fe) and manganese (Mn) are essential cellular constituents but are required in relatively low concentrations in relation to their availability in fresh waters (US EPA, 1997).

### Nitrogen and Phosphorus

Compounds of nitrogen (N) and phosphorus (P) are major cellular components of organisms. Since the availability of these elements is often less than biological demand, environmental sources can regulate or limit the productivity of organisms in aquatic ecosystems. Productivity of aquatic ecosystems can, thus, be managed by regulating direct or indirect inputs of nitrogen and phosphorus with the aim of either reducing or increasing primary production.

Phosphorus is present in natural waters primarily as phosphates, which can be separated into inorganic and organic phosphates. Phosphates can enter aquatic environments from the natural weathering of minerals in the drainage basin, from biological decomposition, and as runoff from human activities in urban and agricultural areas. Inorganic phosphorus, as orthophosphate ($PO_4^{3-}$), is biologically available to primary producers that rely on phosphorus for production and has been demonstrated to be an important nutrient limiting maximum biomass of these organisms in many inland systems. Phosphorus in water is usually measured as total phosphorus, total dissolved phosphorus (i.e., all P that passes through a 0.45µm pore-size filter), and soluble reactive or orthophosphorus.

Nitrogen occurs in water in a variety of inorganic and organic forms and the concentration of each form is primarily mediated by biological activity. Nitrogen-fixation, performed by cyanobacteria (blue-green algae) and certain bacteria, converts dissolved molecular $N_2$ to ammonium ($NH_4^+$). Aerobic bacteria convert $NH_4^+$ to nitrate ($NO_3^-$) and nitrite ($NO_2^-$) through nitrification, and anaerobic and facultative bacteria convert $NO_3^-$ and $NO_2^-$ to $N_2$ gas through denitrification. Primary producers assimilate inorganic N as $NH_4^+$ and $NO_3^-$, and organic N is returned to the inorganic nutrient pool through bacterial decomposition and excretion of $NH_4^+$ and amino acids by living organisms. Nitrogen in water is usually measured as total nitrogen, ammonium, nitrate, nitrite, total Kjeldahl nitrogen (= organic nitrogen + $NH_4^+$), or as a combination of these parameters to estimate inorganic or organic nitrogen concentrations.

Phosphorus and nitrogen are considered to be the primary drivers of eutrophication of aquatic ecosystems, where increased nutrient concentrations lead to increased primary productivity. Some systems are naturally eutrophic, whereas others have become eutrophic as a result of human activities ('cultural eutrophication') through factors such as runoff from agricultural lands and the discharge of municipal waste into rivers and lakes. Aquatic ecosystems can be classified into trophic state, which provides an indication of a system's potential for biomass growth of primary producers. Trophic states are usually defined as oligotrophic (low productivity), mesotrophic (intermediate productivity), and eutrophic (high productivity). Ultraoligotrophic and hypereutrophic states represent opposite extremes in the trophic status classifications of aquatic environments. Although there are many methods for classifying systems into trophic state, a common approach examines concentrations of nutrients across many systems and separates systems according to their rank in the range of nutrient concentrations (Dodds *et al*., 1998). This approach is demonstrated in Figure 12 for river monitoring stations worldwide.

| | Total Phosphorus (mg $L^{-1}$) | | |
|---|---|---|---|
| | Station | Oliogotrophic-Mesotrophic boundary | Mesotrophic-Eutrophic boundary |
| Africa | 12 | 0.21 | 0.49 |
| Americas | 46 | 0.05 | 0.10 |
| Asia | 144 | 0.06 | 0.13 |
| Europe | 116 | 0.10 | 0.32 |
| Oceania | 88 | 0.10 | 0.20 |
| Global | 406 | 0.07 | 0.20 |

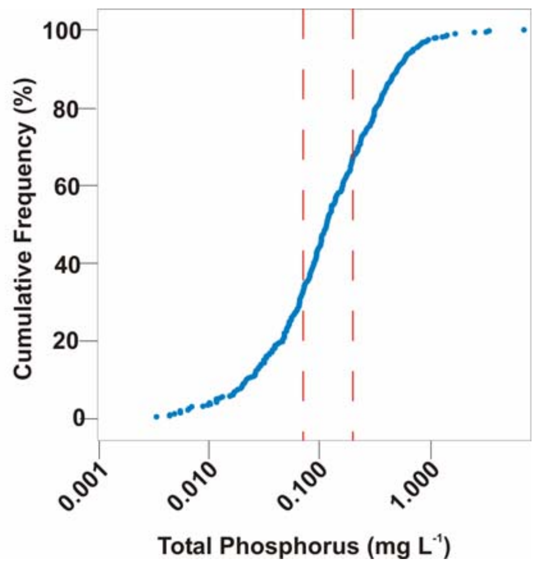



Figure 12. Cumulative frequency diagram of mean total phosphorus concentrations in river monitoring stations. Dashed lines separate distribution of global data into thirds, which can be used to classify systems as oligotrophic (bottom third), mesotrophic (middle third) or eutrophic (upper third). The table shows the boundary concentrations that divide rivers by region.

## Silica

Silica or silicon dioxide ($SiO_2$) is a key micronutrient in diatom production, a very common algal group, and is taken up during the early growing season. Silica concentrations can limit diatom production if concentrations become depleted in surface waters. The depletion of silica tends to occur more often in lakes and reservoirs than in running waters (US EPA, 1997; Cambers and Ghina, 2005). During periods of high biological productivity by diatoms, silica concentrations may be depleted from the surface waters of lakes by more than a factor of ten, as depicted for several lakes and reservoirs in Figure 13. The declines in silica in the surface waters usually lead to a rapid decline in diatom populations.

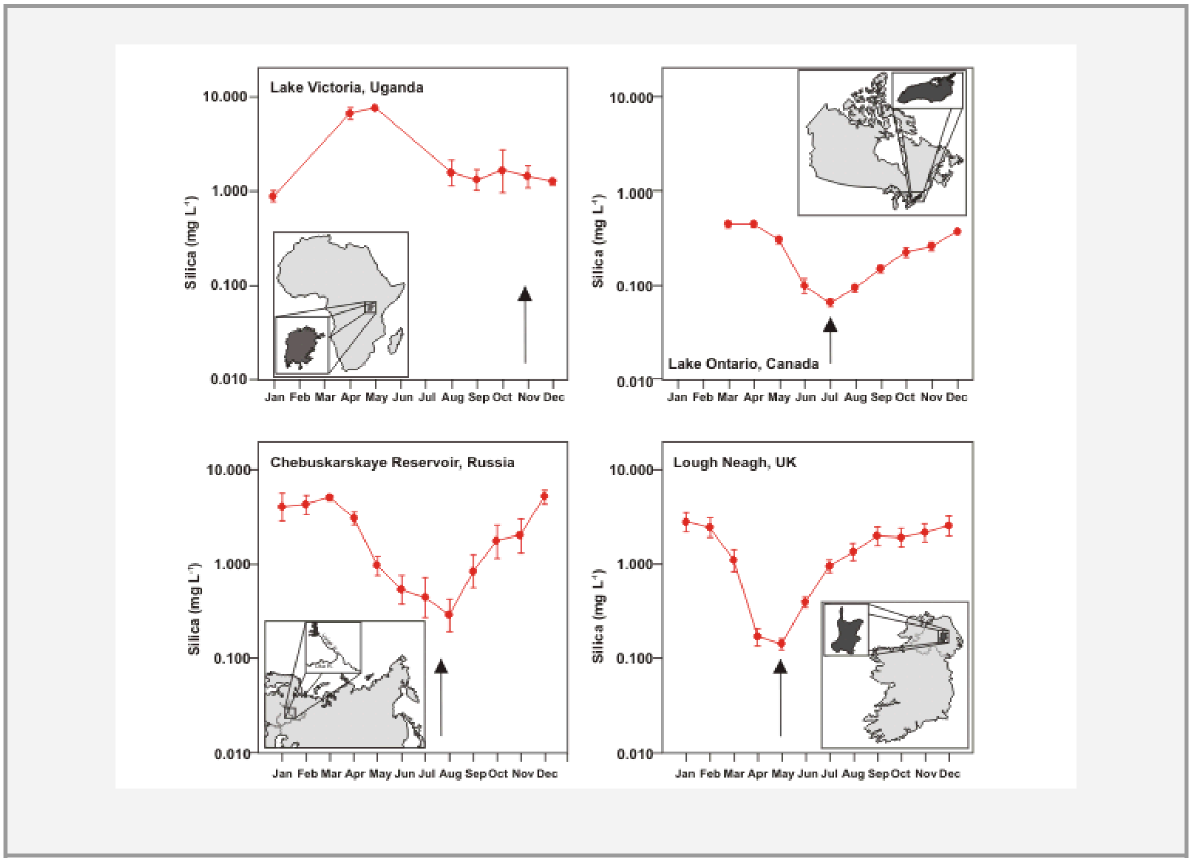



Figure 13. Monthly mean (± 1 standard error) silica concentration in lakes and reservoirs around the world. Black arrows indicate approximate period of silica depletion. Silica concentrations measured at depths of 1, 0, 0.3-0.5, and 10m for Lake Victoria, Lake Ontario, Chebuskarskaye Reservoir, and Lough Neagh, respectively.

### *Metals*

Metals occur naturally and become integrated into aquatic organisms through food and water. Trace metals such as mercury, copper, selenium, and zinc are essential metabolic components in low concentrations. However, metals tend to bioaccumulate in tissues and prolonged exposure or exposure at higher concentrations can lead to illness. Elevated concentrations of trace metals can have negative consequences for both wildlife and humans. Human activities such as mining and heavy industry can result in higher concentrations than those that would be found naturally.

Metals tend to be strongly associated with sediments in rivers, lakes, and reservoirs and their release to the surrounding water is largely a function of pH, oxidation-reduction state, and organic matter content of the water (and the same is also true for nutrient and organic compounds). For example, metal concentrations in Lake Mashu in Japan tended to be elevated near the bottom of the lake where oxidation-reduction states are usually high (Figure 14). Thus, water quality monitoring for metals should also examine sediment concentrations, so as not to overlook a potential source of metal contamination to surface waters.

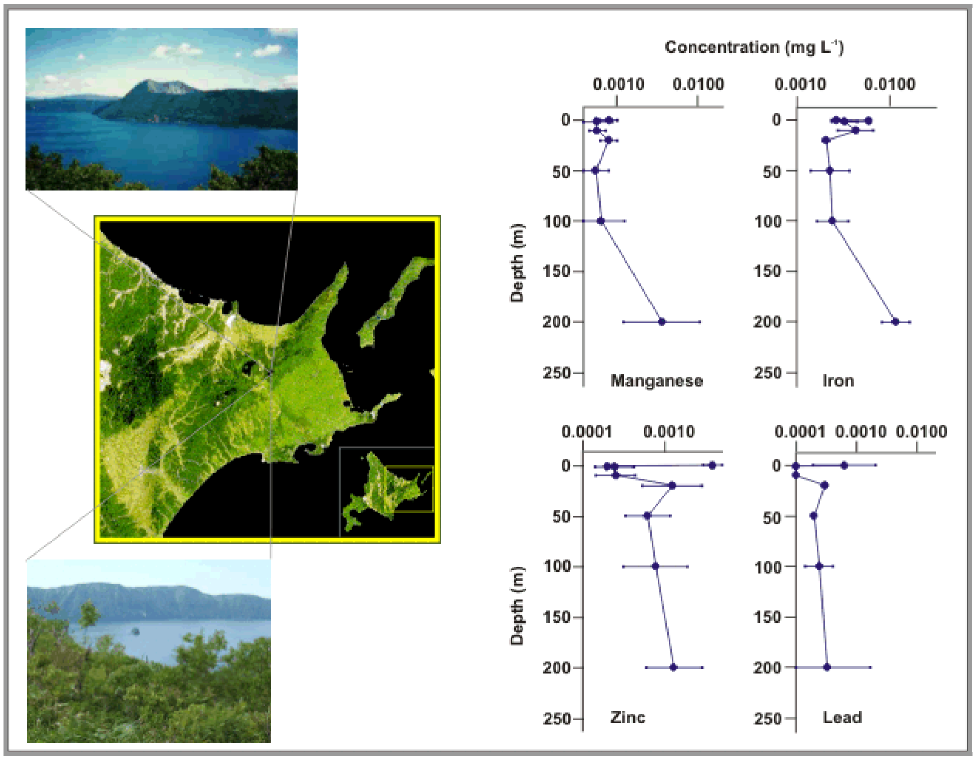



Figure 14. Total metal concentrations plotted against depth in Lake Mashu, Japan, between 1995 and 2002. Data are mean ± 1 standard deviation. Note the increase in iron and manganese near the lake bottom, where oxidation-reduction states are usually high.

Metals in water can pose serious threats to human health. In particular, arsenic, a semi-metallic element which occurs naturally in some surface and ground water sources, may lead to development of skin lesions and cancer in people exposed to excess concentrations through drinking water, bathing water, or food. Arsenic can be mobilized from host minerals through anaerobic microbial respiration (i.e., bacteria that are able to respire in the absence of oxygen), as long as sufficient organic carbon is available to sustain metabolism. There are certain well-documented 'hot spots' where arsenic in groundwater tends to be high, including Bangladesh and India and, to a lesser extent, Vietnam and Cambodia, (Charlet and Polya, 2006). However, arsenic is by no means ubiquitous at elevated concentrations: only one out of 22 groundwater monitoring stations examined had levels above the World Health Organization drinking water guideline (Figure 15). The monitoring of metals in surface and ground water supplies, particularly those intended for human consumption, provides background information on the suitability of the resources for consumption.

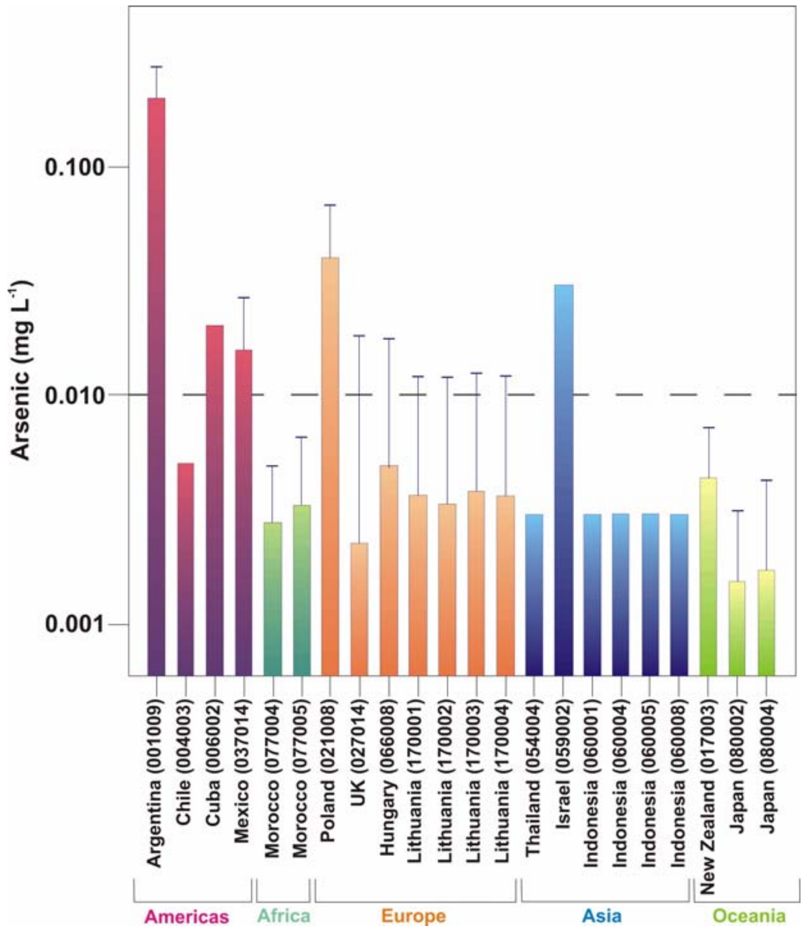



Figure 15. Arsenic in groundwater samples from monitoring stations around the world. Data are mean ± 1 standard deviation. Dashed line is WHO drinking water quality guideline.

## Mercury

Mercury is a metal found naturally in the environment but human activities have greatly increased its atmospheric concentration, accounting for approximately 75 percent of worldwide emissions. Anthropogenic sources of mercury in the environment include incinerators (municipal waste), coal-burning facilities (electrical generation), industrial processes (older methods for producing chlorine and caustic soda), and some consumer products (e.g., batteries, fluorescent lights, thermometers). The form of mercury of most concern from a water quality perspective is $Hg^{2+}$ because it dissolves quickly in water and is consequently the form most often found in aquatic ecosystems. Mercury in water is usually measured in its total or dissolved forms, as shown for several river systems from around the world in Figure 16. Similar to many chemical parameters in surface waters, mercury concentrations closely track discharge values, as demonstrated for the Elbe River, Germany, in Figure 17.

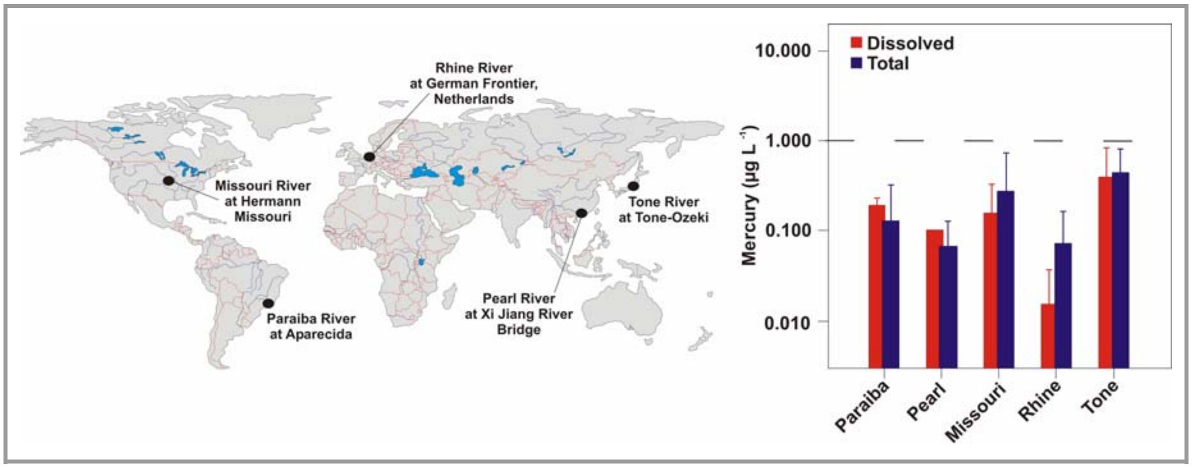



Figure 16. Dissolved and total mercury concentrations in rivers of Brazil (Paraiba), China (Pearl), United States (Missouri), Netherlands (Rhine) and Japan (Tone). Data are mean ± 1 standard deviation. Dashed line is World Health Organization drinking water quality guideline for total mercury. Note that mean mercury concentrations are below guideline values at all monitoring stations.

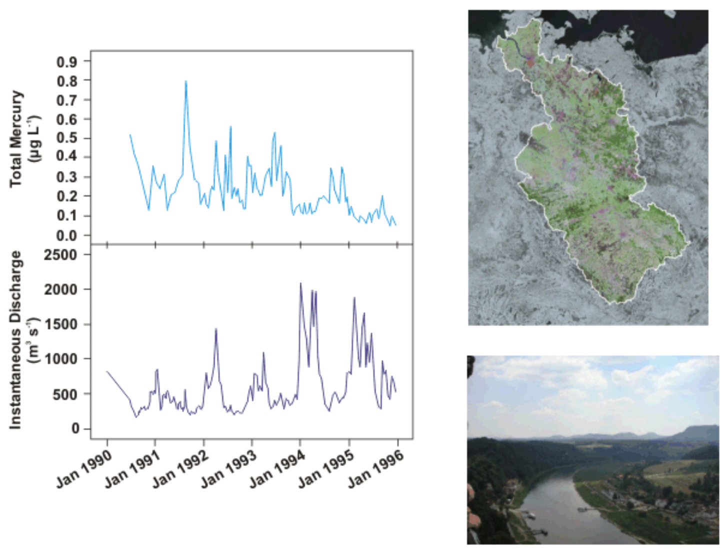



Figure 17. Mercury (top) and instantaneous discharge (bottom) in the Elbe River at Zollenspieker, Germany in the early 1990s. Notice that peaks in mercury concentrations tend to correspond to low discharge events and that mercury in 1994 and 1995 was lower than in previous years, probably due to high discharges in those years.

When mercury is found in water some of the micro-organisms present transform it into methylmercury, which is very toxic. Methylmercury tends to remain dissolved in water and does not travel far in the atmosphere. However, it can be converted back into elemental mercury and re-emitted to the atmosphere. This 'leap-frog' effect may occur a number of times, dispersing mercury over great distances. Mercury is of concern because it accumulates in the tissues of wildlife and humans, sometimes at tens of thousands of times the concentration found in the water source, causing reproductive and neurological problems.

## *Organic Matter*

Organic matter is important in the cycling of nutrients, carbon and energy between producers and consumers and back again in aquatic ecosystems. The decomposition of organic matter by bacteria and fungi in aquatic ecosystems, inefficient grazing by zooplankton, and waste excretion by aquatic animals, release stored energy, carbon, and nutrients, thereby making these newly available to primary producers and bacteria for metabolism. External subsidies of organic matter that enter aquatic ecosystems from a drainage basin through point sources such as effluent outfalls, or non-point sources such as runoff from agricultural areas, can enhance microbial respiration and invertebrate production of aquatic ecosystems.

Organic matter affects the biological availability of minerals and elements, and has important protective effects in many aquatic ecosystems, by influencing the degree of light penetration that can enter.

### Organic Carbon

Organic carbon refers to the myriad organic matter compounds in water. Dissolved organic carbon (DOC) is organic material from plants and animals that has been broken down to very small sizes, usually less than 0.45µm in diameter. DOC originating from a drainage basin is often composed of humic acids and may be yellow or brown in colour, which can be detected in a sample of water. DOC produced *in situ* usually is not pigmented, and the pigmentation of DOC entering a system may be lost due to degradation by light, as in Picture 1. High DOC waters tend to have lower pH values, as shown for several monitoring stations along the Rhine River in Europe (Figure 18).

Picture 1. Coloured water collected from an inflowing creek of Redberry Lake, Saskatchewan, Canada (left sample, DOC = 15mg $L^{-1}$) and of clear, non-coloured water from the pelagic zone of Redberry Lake itself (right sample, DOC = 35mg $L^{-1}$). Note that normally coffee-coloured

pigmentation of DOC in the lake water has been lost due to photobleaching (Photo: M.J. Waiser).

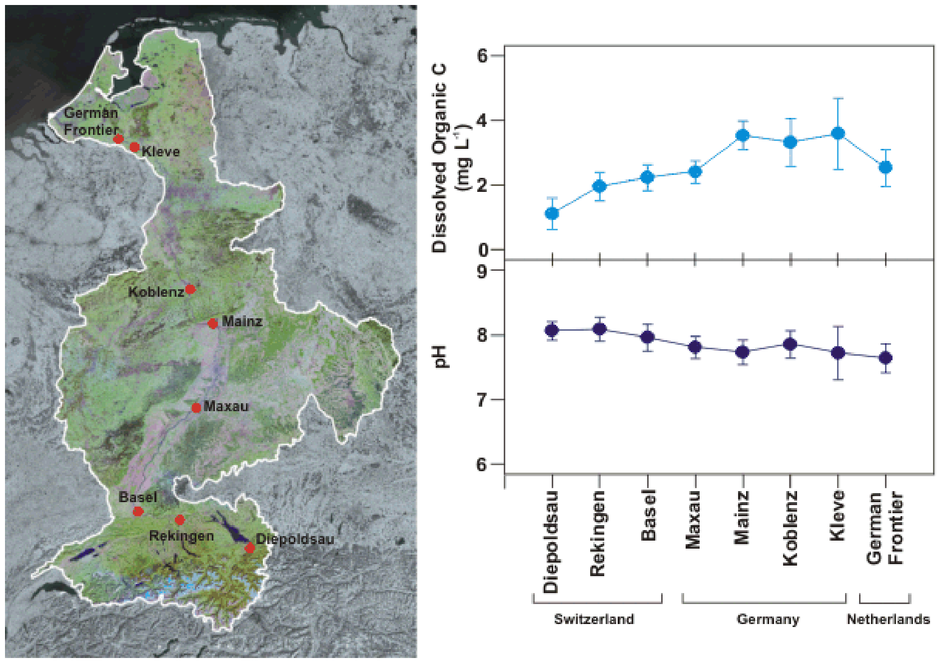



Figure 18. Dissolved organic carbon (C) and pH along the length of the Rhine River and flowing through Switzerland, Germany and the Netherlands. Note the general increase in DOC and the concurrent slight decrease in pH along the length of the river.

## Biochemical Oxygen Demand and Chemical Oxygen Demand

Many aquatic ecosystems rely heavily on external subsidies of organic matter to sustain production. However, excess inputs of organic matter from the drainage basin, such as those that may occur downstream of a sewage outfall, can upset the production balance of an aquatic system and lead to excessive bacterial production and consumption of dissolved oxygen that could compromise the integrity of the ecosystem and lead to favourable conditions for growth of less than ideal species.

Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are two common measures of water quality that reflect the degree of organic matter pollution of a water body. BOD is a measure of the amount of oxygen removed from aquatic environments by aerobic micro-organisms for their metabolic requirements during the breakdown of organic matter, and systems with high BOD tend to have low dissolved oxygen concentrations, as shown for two Indonesian rivers in Figure 19. COD is a measure of the oxygen equivalent of the organic matter in a water sample that is susceptible to oxidation by a strong chemical oxidant, such as dichromate (Chapman, 1996).

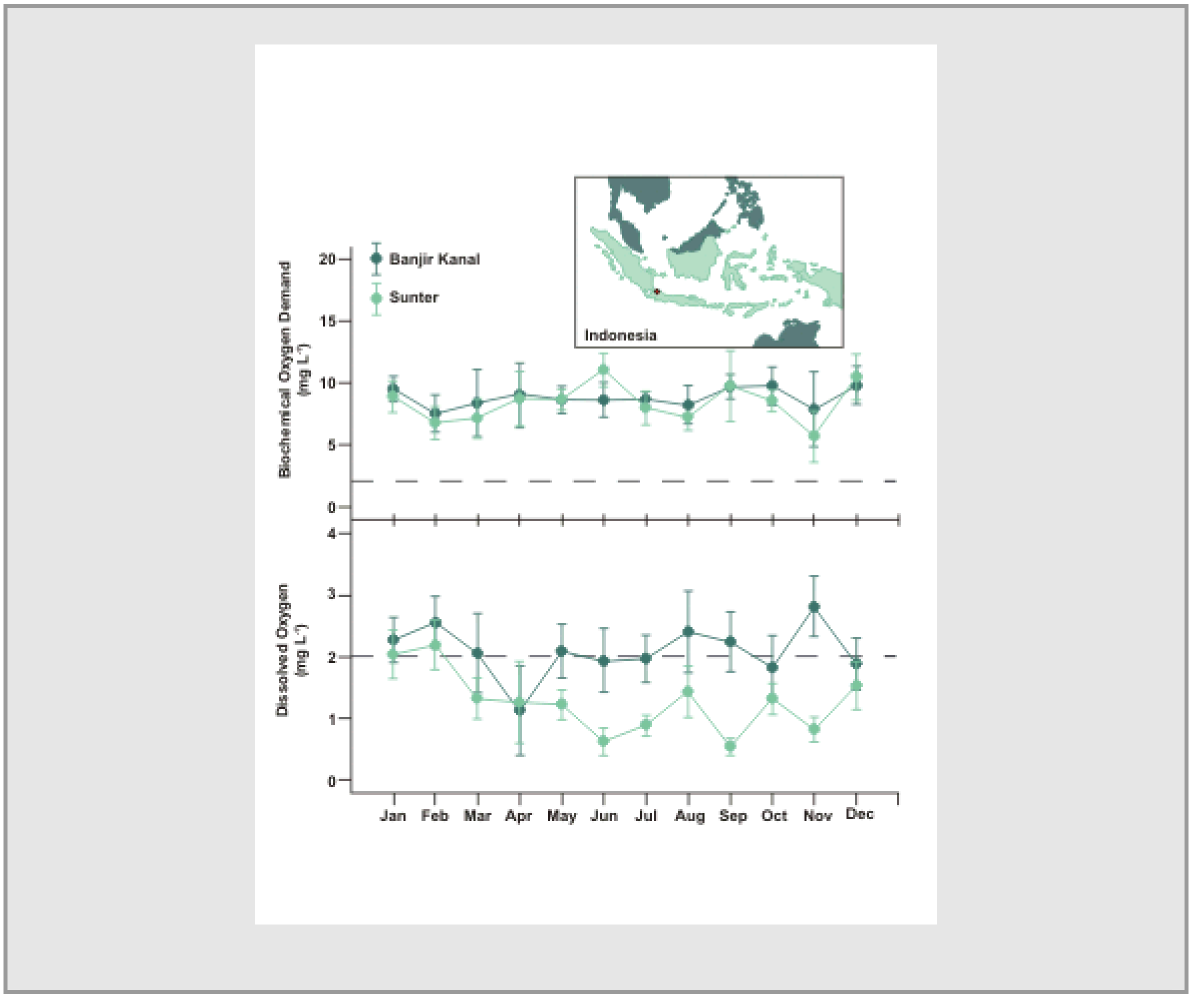



Figure 19. BOD and DO in two Indonesian rivers, plotted as monthly means (± 1 standard error). Dashed lines indicate the BOD concentration below which a system is considered to be unpolluted and the DO concentration below which most fish die (Chapman, 1996). Note that both rivers are typical of polluted systems: BOD concentrations are well-above the threshold for unpolluted systems, and DO concentrations are near or below the level at which most fish die.

Although BOD and COD are usually at or near analytical limits of detection in relatively undisturbed systems, water samples taken near points of organic matter pollution often yield very high observations, as demonstrated for several surface water monitoring stations in Spain (Figure 20).

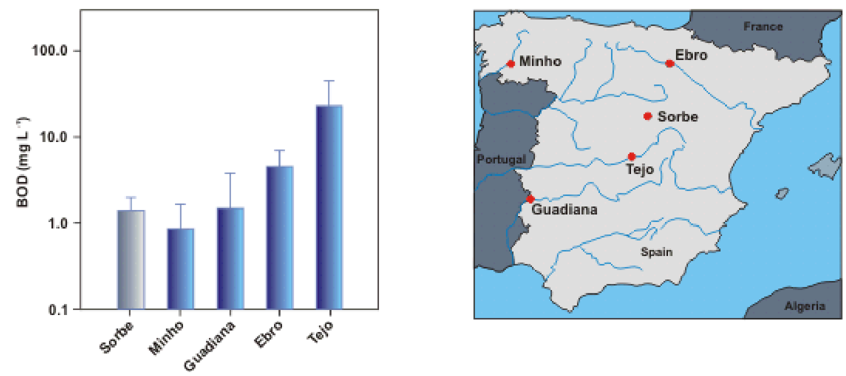



Figure 20. BOD (in mg $L^{-1}$) at one baseline (Sorbe River) and four impact (Minho, Guadiana, Ebro and Tejo Rivers) monitoring stations in Spain. Data are mean ± 1 standard deviation.

### *Biological components*

Organisms, populations, and communities composed of different species make up the biological diversity of aquatic ecosystems. From single-celled microbes such as viruses, bacteria, protists, and fungi, to multi-cellular organisms such as vascular plants, aquatic invertebrates, fish and wildfowl, the community of organisms that reside within and near aquatic ecosystems simultaneously plays a vital role in regulating biogeochemical fluxes in their surrounding environment and is influenced by these same biogeochemical fluxes. Aquatic organisms, often considered 'engineers' of aquatic ecosystems, not only react to physical and chemical changes in their environment, but also they can drive such changes and have important roles in cleansing and detoxifying their environment (Ostroumov, 2005). The entire biological diversity of aquatic environments ensures that ecosystems can continue to function normally: shifts in species composition through species losses or biological invasions can lead to physical and chemical changes in the environment that may have detrimental effects on both the community of organisms residing within the ecosystem and on humans that rely upon the system for water supply and other activities. The diversity of aquatic ecosystems can also be influenced by physical and chemical changes in the environment.

There is considerable duplication of function in aquatic food webs, where several species and trophic levels may perform similar functions of self-purification of a body of water. For example, both bacteria and fungi have roles in the chemical breakdown of pollutants in aquatic environments, and filtering of water is performed by invertebrates living in both benthic and pelagic environments of a system (Ostroumov, 2005). Although this duplication of function provides a type of back-up for the maintenance of ecological services, it is not a guarantee that ecosystems are protected against further degradation.

Losses of sensitive species may have feedback effects on other resident organisms that can lead to catastrophic shifts in the composition of aquatic communities and the functions they provide. As such, the overall diversity of biological communities enables many ecosystem processes to function normally and in a stable state. Loss of diversity may lead to declines in ecosystem function as well as shifts to alternate stable states (Ostroumov, 2005; Scheffer *et al*., 2001). A common example of a dramatic shift in ecosystem condition to an alternate stable state that has been attributed to water pollution is the shift from a clear-water, vascular plant dominated state to a turbid, phytoplankton-dominated state in many shallow lakes (Scheffer *et al*., 2001).

Given the importance of biological communities to water quality, water pollution should be considered as a biological issue since it impairs the ability of resident and non-resident organisms to use resources provided by the ecosystem and to maintain ecological services. Physical loss of habitat and changes in the chemical composition of water can inhibit a species' ability to grow, reproduce, and interact with other species in the ecosystem. Excessive sediment loads in rivers, for example, disturb the life-cycle of fishes, by interfering with respiration and covering spawning areas, and when deposited, can smother benthic organisms. Various pollutants have differing effects ranging from inducing catastrophic mortality to chronic illness, in addition to the effects of bio-accumulation through the food chain.

The assessment of biological communities present in an aquatic environment reflects the quality of the ecosystem. Biomonitoring is a tool for assessing environmental quality because biological communities integrate the effects of different stressors and thus, provide a broad measure of their aggregate impact. Biota also integrate stressors over time and provide an ecological measure of fluctuating environmental conditions. Widespread use of biomonitoring techniques has resulted in part from public interest in the status of individual species and cost effectiveness of sampling regimes. The monitoring of biological communities can be done at a variety of trophic levels including micro-organisms (bacteria, protists, and viruses), primary producers (algae and vascular plants), primary consumers (invertebrates) and secondary consumers (fish) (Rosenberg, 1998; Reynoldson *et al*., 1997; Barbour *et al*., 1999).

### Microbes

Microbial communities of bacteria, viruses, protists and fungi are ubiquitous in aquatic environments, but it is only in recent years that scientists have recognized the importance of their contribution to aquatic ecosystem functioning. Microbial populations are typically characterized by high absolute population sizes, short generation (i.e., reproduction) times, and high dispersal capabilities (Dolan, 2005). Most microbes are heterotrophic organisms, meaning they require organic carbon to fuel their metabolism. Bacteria and fungi are important decomposers of organic matter in aquatic ecosystems, releasing nutrients and minerals to the water column that can be used to fuel metabolism of other organisms. Although the study of aquatic viruses is still in its infancy, these viruses appear to infect primarily bacterial and single-celled algae and to have important roles in regulating production and diversity of the microbial food web (Wommack and Colwell, 2000).

The majority of microbes inhabiting aquatic ecosystems are completely benign to humans and have important roles in aquatic ecosystem functioning. However, microbial contamination of surface and ground waters by pathogenic organisms is probably the most important water quality issue in the developing world, where access to safe, clean water for drinking, bathing and irrigation is often unavailable. The World Health Organization identifies the greatest human health risk of microbial contamination as being through the consumption of water contaminated by human or animal faeces (WHO, 2004).

Monitoring microbes in surface or ground waters is used to detect the presence of pathogenic organisms in order to prevent disease. There are a number of broad classes of such microbes including bacteria, protozoa, parasitic worms, fungi, and viruses. Indicator micro-organisms are used to suggest the presence of pathogens. The organisms most often used are faecal indicators: organisms that indicate the presence of faecal contamination from animal or human wastes. Tests used to indicate the presence of pathogenic organisms include those for total coliforms, faecal coliforms, or for *E. coli* specifically (Ashbolt *et al*., 2001). For example, Figure 21 shows average concentrations of total and faecal coliform bacteria in the Po River, Italy, for samples collected between 1979 and 1995. It is important to note that these measures are only indicators, and may not detect all pathogens in a body of water (Tallon *et al*., 2005).

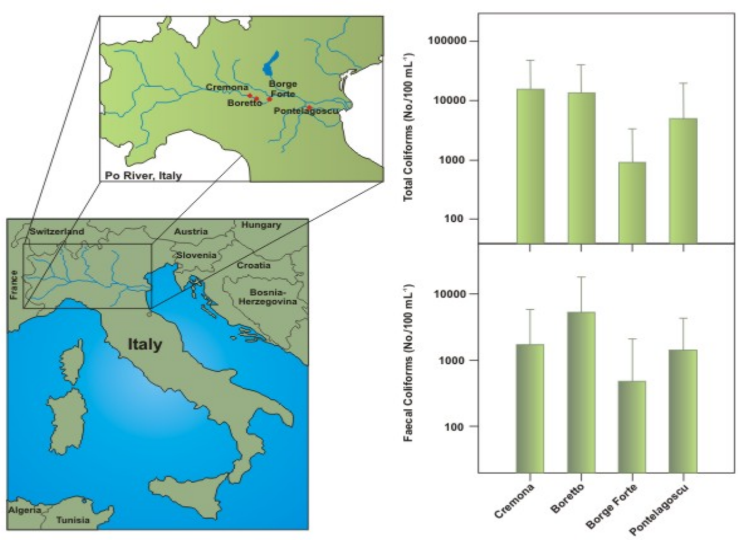



Figure 21. Mean (± 1 standard deviation) total and faecal coliform concentrations at four stations in the Po River, Italy. Data were collected as part of routine monitoring of these stations between 1979 and 1995.

When available, water treatment facilities have the potential to reduce the presence of coliform bacteria in samples from very high concentrations to values below levels of analytical detection. Although water treatment facilities exist in nearly all cities of the developed world, the supply of safe drinking water and sanitation facilities is still lacking in many parts of the developing world. Figure 22 demonstrates how total and faecal coliform concentrations are slightly, but consistently, higher in the Ravi River downstream of the city of Lahore, Pakistan, when compared to upstream values.

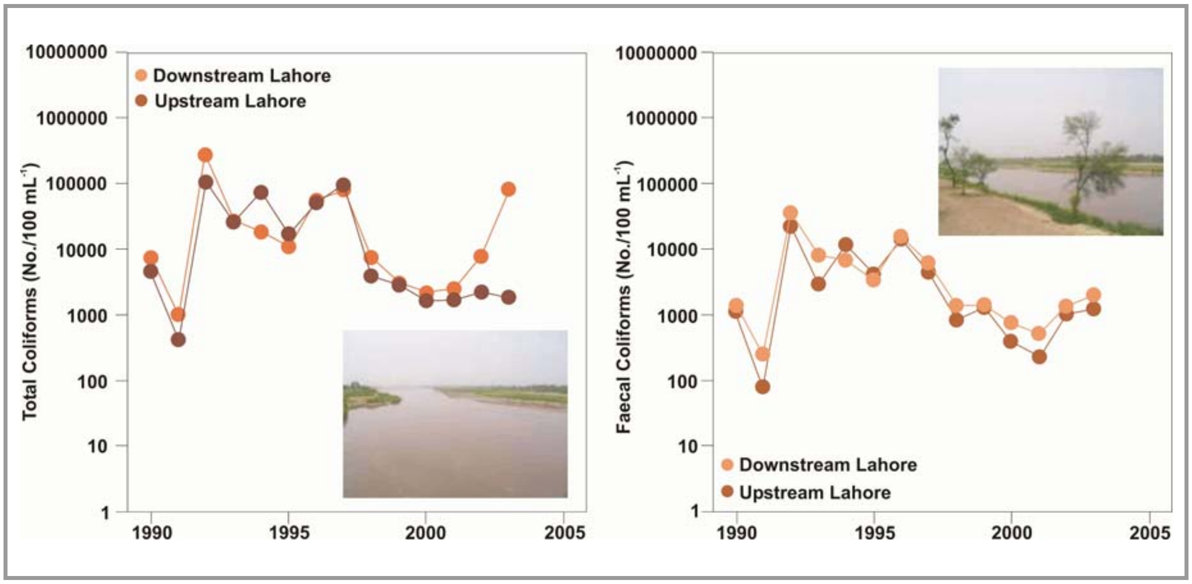



Figure 22. Total and faecal coliform concentrations in the Ravi River, upstream and downstream of the City of Lahore, Pakistan. Data are annual mean concentrations. Note that despite differences being small, coliform concentrations downstream of Lahore are consistently greater than upstream concentrations.

## Algae and Aquatic Vascular Plants

Algae and aquatic vascular plants (macrophytes) make up the primary producers of aquatic ecosystems. Algae are unicellular organisms that reside either suspended in the water column (phytoplankton) or attached to surfaces (periphyton). Aquatic vascular plants are usually rooted to a substrate but may also be free-floating. As primary producers, algae, and to a lesser extent, aquatic vascular plants, form the basis of aquatic food webs. Vascular plants have the additional role of providing habitat and shelter for fish and invertebrates in the littoral zones of lakes and rivers. Algal and vascular plant abundance in aquatic ecosystems is primarily controlled by the availability of the nutrients nitrogen and phosphorus in the water column and in sediments, although light and temperature also play important roles in determining the distribution and abundance of these organisms.

Algae and aquatic vascular plants generally have rapid reproduction rates and very short life cycles, making them valuable indicators of short-term environmental impacts. Algae and aquatic plants, as primary producers, are most directly affected by physical and chemical factors and are sensitive to pollutants which may not visibly affect other aquatic assemblages, or that may only affect other organisms at higher concentrations (Barbour *et al*., 1999). Sampling such plants is relatively easy, inexpensive and non-disruptive, and standardized methods exist for comparisons within and between regions. Species diversity and community abundance (often measured as chlorophyll *a* in algae) are often used as indicators of algal and aquatic plant growth and production. As an example, Figure 23 depicts the regular seasonal cycles in algal biomass at three monitoring stations in the Odra River, Poland.

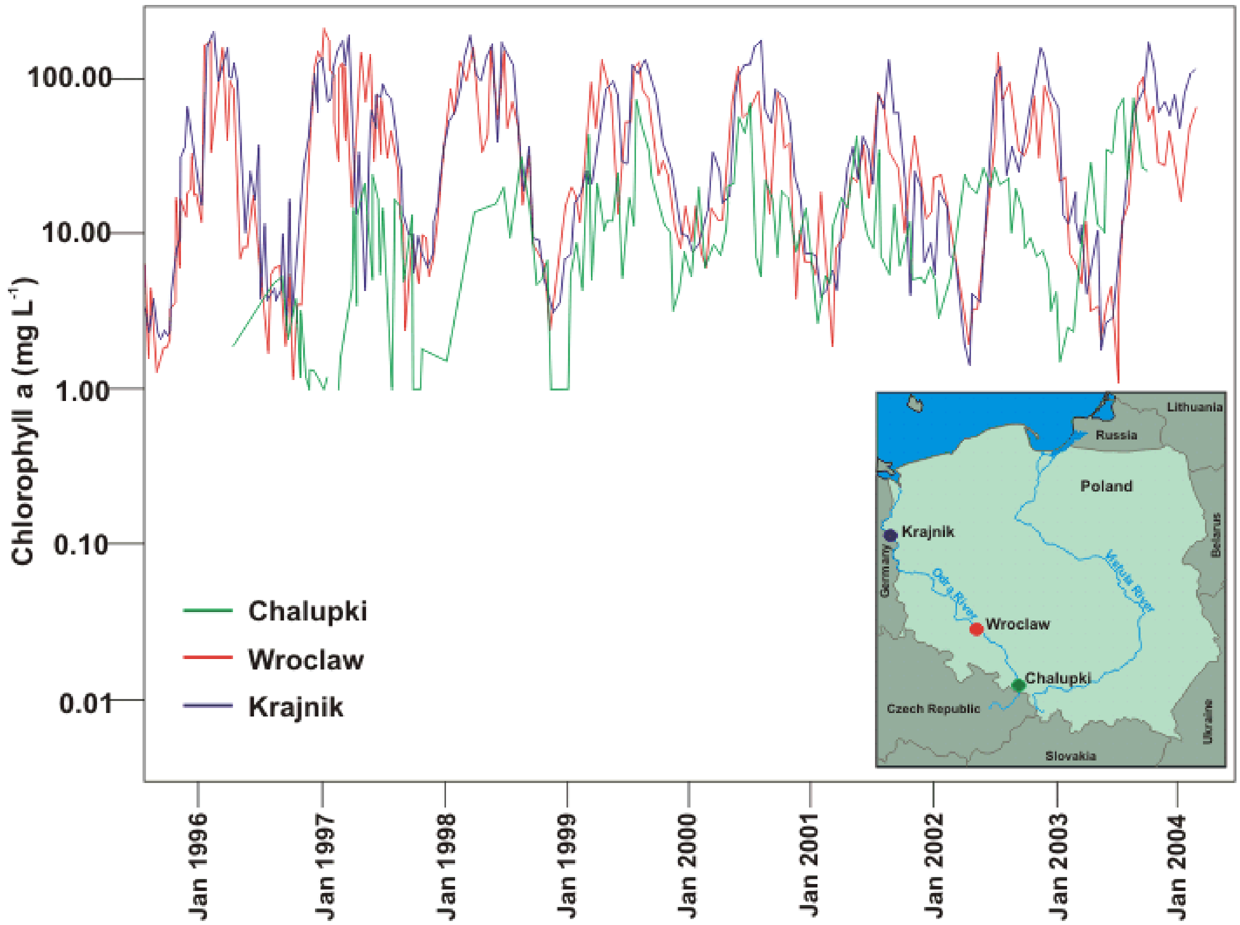



Figure 23. Long-term monitoring of algal biomass, measured as chlorophyll *a*, at three stations in the Odra River, Poland. Note the strong seasonal cycles in chlorophyll *a* from year to year at each station.

## Invertebrates: Zooplankton and Benthic Macroinvertebrates

Aquatic invertebrates are consumers that feed, primarily, on bacteria, algae, and detrital matter that is both produced within and enters from the surrounding catchment. Zooplankton is the community of invertebrates that is suspended in the water column, whereas lake and river bottoms are inhabited by benthic macroinvertebrates. Invertebrates have the ability to control the abundance of algae through grazing, and are an important food source to organisms in higher trophic levels, such as fish and other predatory invertebrates.

Invertebrate assemblages are good indicators of localized conditions because many have limited migration patterns or are sessile (non-motile) and, thus, are useful for examining site-specific impacts. Individual invertebrate species respond differently to environmental changes. Changes in the environment will be reflected in changes in the species assemblage both spatially and temporally (i.e., affected and unaffected sites over time). Therefore, these assemblages can be used to help assess environmental degradation from both single and cumulative sources. Inexperienced biologists can be easily trained in invertebrate taxonomy to reasonably low levels of taxonomic resolution, and sampling methodologies are relatively simple and inexpensive to undertake (Barbour *et al*., 1999).

#### Fish

Fish are the top predators of most aquatic ecosystems, depending on lower feeding groups for food, and as such play important roles in top-down control of growth and production of lower feeding groups. Fish are important not only for ecosystem function, but also may provide socioeconomic value in the form of fishery resources for people. Loss of fish species due to changes in water quality or over-fishing may result in dramatic shifts in ecosystem dynamics, as grazing pressure on invertebrates and algae can be released, enabling rapid growth and potential blooms of algal populations.

Fish communities can be used to indicate longer term or wider ranging effects of changes in the aquatic environment because many fish species are relatively long-lived and mobile. They tend to integrate effects of lower trophic levels, thereby providing a measure of integrated environmental health. Fish are important for assessing contaminants in ecosystems since they generally represent the top of the food chain and are susceptible to bioaccumulation and bio-magnification of heavy metals and synthetic organic contaminants. They are relatively easy to collect and identify to species level and can sometimes be collected and released unharmed (non-destructive sampling) when fish tissues and organs are not required for analysis (Barbour *et al*., 1999).

### *Organic Contaminants*

Organic contaminants are primarily human-produced chemicals that enter natural environments through pesticide use, industrial chemicals, and as by-products of degradation of other chemicals. Persistent Organic Pollutants (POPs) tend to persist in the environment and become widely distributed geographically, bioaccumulate through the food web, and pose the risk of causing severe adverse effects to human health and the environment. The Stockholm Convention on Persistent Organic Pollutants, which entered into force in 2004, is a global treaty to protect human health and the environment from POPs, in which signatory governments will take measures to eliminate or reduce the release of POPs into the environment. The POPs identified under the Stockholm Convention are listed in Table 3. Although by no means an exhaustive list of potential POPs entering the environment, the named compounds are often referred to as the ‘dirty dozen’: that is, those chemicals that pose the greatest known threat to the environment and human health. The effects of many other POPs are still being researched.

Table 3. Twelve Persistent Organic Pollutants (POPs) scheduled to be phased out and eliminated under the Stockholm Convention.

| Substance | Class |
|---|---|
| Aldrin | Pesticide |
| Chlordane | Pesticide |
| Dieldrin | Pesticide |
| Endrin | Pesticide |
| Heptachlor | Pesticide |
| Hexachlorobenzene | Pesticide / industrial chemical / by-product |
| Mirex | Pesticide |
| Toxaphene | Pesticide |
| Polychlorinated biphenyls (PCBs) | Industrial chemical / by-product |
| DDT | Pesticide |
| Dioxins | By-product |
| Furans | By-product |

## Pesticides

Pesticides can target a number of different types of organisms including plants, insects, fungi, nematodes, and rodents. Pesticides are important for the protection of crop production in agricultural regions and for the protection of human health in many parts of the world through pest control (e.g., mosquito control to prevent malaria). However, pesticides also have detrimental effects on natural ecosystems; among the 12 toxic substances that have been identified in the Stockholm Convention, nine are classed as organochlorine pesticides.

Pesticides contain both the active ingredient used to kill the pest species as well as contaminants that exist as impurities in the active ingredient. These compounds also contain additives that are mixed with the active ingredient such as wetting agents, diluents or solvents, extenders, adhesives, buffers, preservatives and emulsifiers. When these compounds enter natural systems they are degraded through chemical, photochemical, or microbial processes resulting in breakdown products. Figure 24 shows peaks in atrazine concentration in two rivers of the Netherlands in June of one year, followed by a gradual decrease in concentration that can be attributed to breakdown of the chemical as well as hydrological flushing through the system. Once pesticides have entered the environment, they or their breakdown products may persist for many years, can be difficult or impossible to remove, and in some cases may be more harmful to the environment than the parent compounds. All of the breakdown substances can influence both ecosystem and human health (Ongley, 1996).

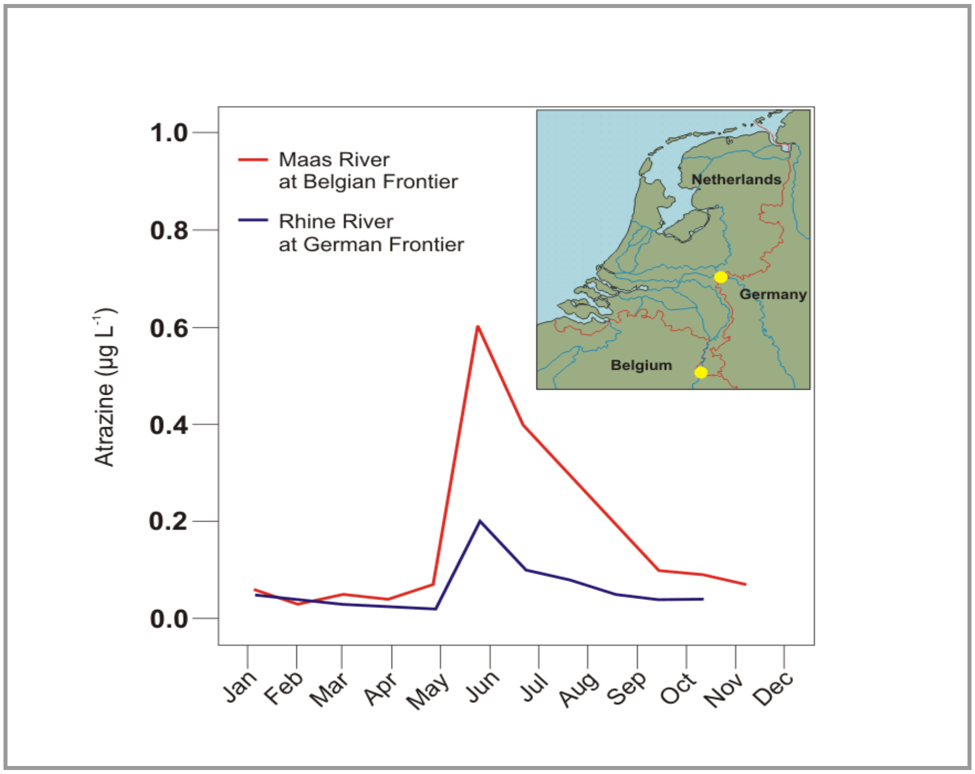



Figure 24. Atrazine concentrations in two rivers of the Netherlands, sampled in 1994. Atrazine is an herbicide used to control weed growth. It is commonly detected in surface and groundwaters. Note the peak in concentrations at both stations around June, when atrazine was most likely applied to the surrounding landscape for weed control. Concentrations at both stations were consistently below the World Health Organization drinking water quality guideline for atrazine of 2µg $L^{-1}$. Because of human health concerns surrounding the detection of atrazine in drinking water supplies, its use has been banned in several countries, including the Netherlands.

## Polychlorinated Biphenyls

Polychlorinated Biphenyls (PCBs) are synthetic oils manufactured for use in electrical transformers, hydraulic oils, and lubricants. These substances were found to be carcinogenic and have been banned from use in many countries. However, they are extremely persistent in the environment and can still be found in the tissues of aquatic organisms at levels that exceed consumption guidelines (Paul and Meyer, 2001). PCBs tend to associate with sediment particles. As industrial sources have mostly been eliminated in developed countries, it is assumed they enter watercourses through non-point sources.

## Oil and Grease

Oil and grease are general terms used to describe crude or refined petroleum products, as well as biological lipids and mineral hydrocarbons. Each type of oil has different physical and chemical properties that will affect its distribution, how quickly it breaks down in the environment and its toxicity to aquatic life (US EPA, 1999). Most research on the effects of oil and grease in aquatic environments has focused on marine environments, although inland aquatic ecosystem studies are becoming more numerous (Akaishi *et al*., 2004; Pettigrove and Hoffmann, 2004; Bhattacharyya *et al*., 2003) and oil and grease are included in some national water quality monitoring programmes. Mexico is one country that monitors oil and grease concentrations, and declines in concentrations were noted at several stations between the early and mid-1990s (Figure 25).

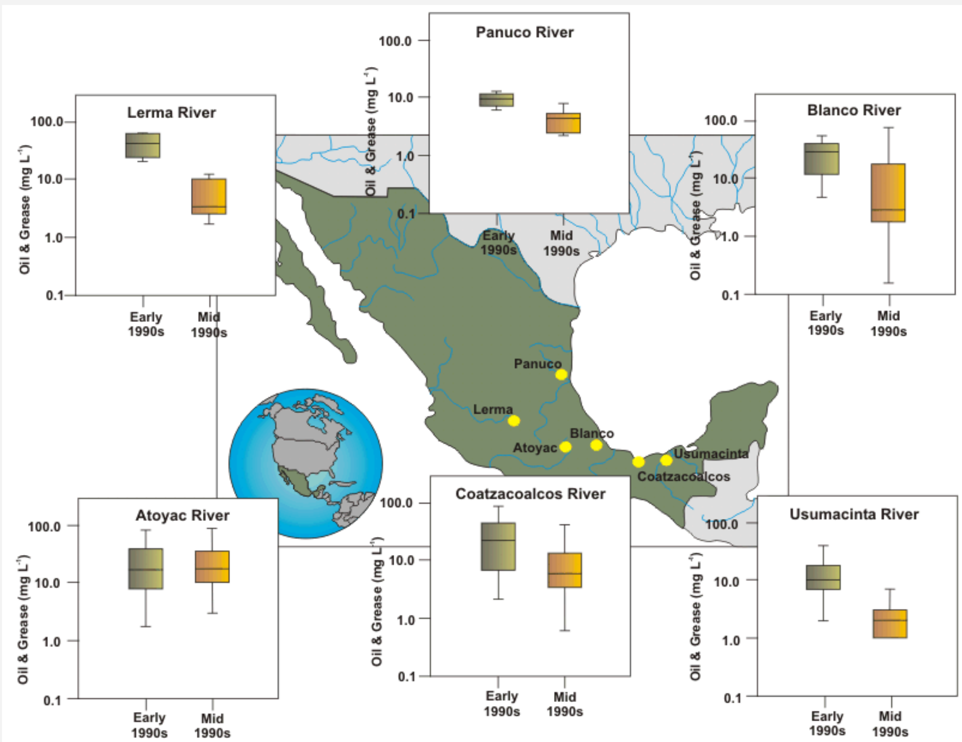



Figure 25. Oil and grease at six river monitoring stations in Mexico. Data collected in early and mid-1990s show a general decline in oil and grease concentrations in most systems over the sampling period. Boxes depict median and 25th and 75th percentiles (mid, bottom, and top of boxes, respectively) and 'whiskers' represent 10th and 90th percentile of data distribution.

Oil and grease can affect aquatic organisms in a number of ways. They can kill directly through coating and asphyxiation, contact poisoning, or through exposure to water-soluble components. Oil and grease can have population effects through the destruction of more sensitive juvenile life-stages or through the reduction of prey species. Oil is also capable of causing sub-lethal and stress effects, carcinogenic and mutagenic effects, and can affect the behaviour of individual organisms. Reductions in diversity and abundance of aquatic fauna have been associated with oil-laden refinery effluents, but the effects on aquatic plants is less clear (Wake, 2005).

## *Hydrological Variables*

The quantity of water contained within a system and its recharge rate affect the chemical and biological properties of all aquatic environments. Water levels and residence times in lakes, reservoirs and wetlands influence nutrient and ionic concentrations of the water and determine the physical extent over which biological production can occur. Changes in water levels tend to be most dramatic in reservoirs in which drawdown is a regular occurrence during dry seasons. Extended periods of drought in many areas can lead to reductions in water levels of all aquatic environments, and evaporative losses of water can lead to the concentration of mineral salts in systems, leading to the salinization of environments that would otherwise normally be considered to contain fresh water.

### Discharge (Stream Flow)

Although not technically a measure of water quality, discharge is an important parameter to monitor because of its direct influence on the chemical composition of a riverine environment and its receiving waters.

Discharge is directly related to the amount of water moving from a watershed into a stream channel and can be defined as the volume of water that moves over a designated point in a stream over a fixed period of time. Discharge is affected by weather: increasing during rainstorms and spring snow melt and decreasing during dry periods. Annual, seasonal and even daily cycles in discharge, as depicted in Figure 26, drive fluxes in suspended and dissolved materials in rivers and streams and the rate of delivery of these materials to points further downstream.

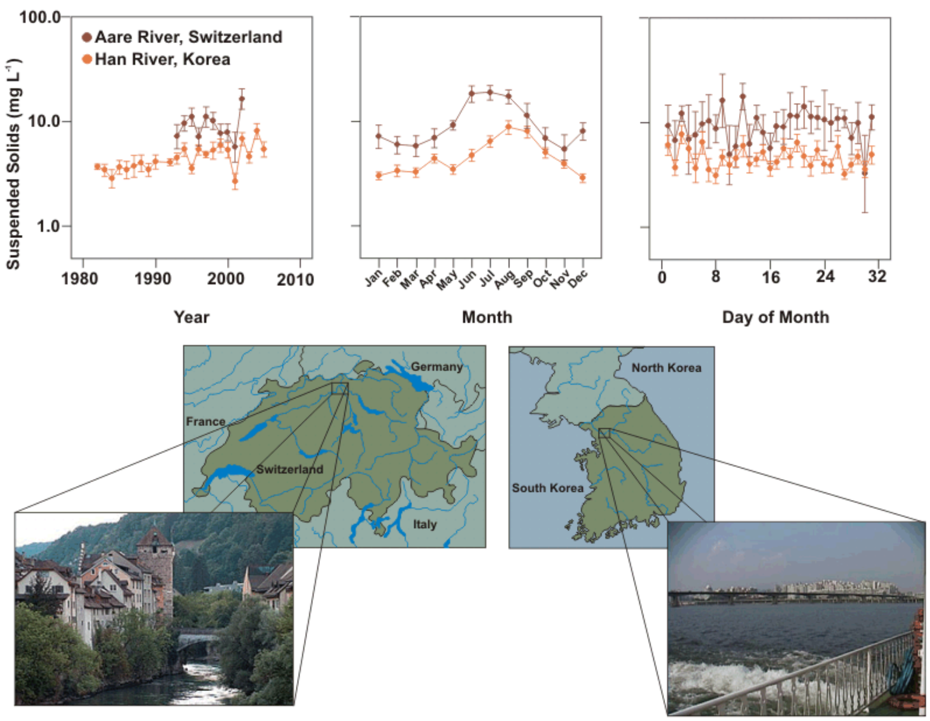



Figure 26. Temporal trends in suspended solids in the Aare River, Switzerland, and the Han

River, Korea. Data are annual, monthly, and day of month means with standard deviations.

Water withdrawals for uses such as irrigation, industry, or municipal extractions for household uses can seriously deplete the flow in a system. Dams used for electric power generation, particularly facilities designed to produce power during periods of peak need, often block the flow of a stream and release it in a surge (Smakhtin *et al*., 2003).

Stream velocity, which increases as the volume of water in a stream increases, determines the kinds of organisms and habitats that can be found in that stream. Some organisms prefer fast moving streams, whereas others prefer slow moving waters. Stream velocity affects the amount of silt and sediment carried by the stream. Sediment in slow-flowing streams will settle to the stream bottom, whereas sediment in fast-moving waters will remain suspended in the water column, eventually settling in lakes, reservoirs, or near shore marine environments, where they can be essential in the maintenance of deltas and biological productivity within these environments. Streams with higher water velocities, especially if they have a coarse substrate, will tend to have higher levels of dissolved oxygen than slow streams with smooth bottoms. Flow can also influence fluctuations of instream water temperature, as temperature is more heavily influenced by atmospheric conditions during periods of low flow.

Discharge influences the susceptibility of a stream to pollution. Large, swiftly flowing rivers can receive pollution discharges and, through dilution, be little affected. Small, slow-flowing streams have a reduced capacity to attenuate and degrade wastes. However, the popular notion that “the solution to pollution is dilution” is dangerous because it does not take into account effects on receiving waters or sediments where the accumulation of pollutants may have significant negative impacts.

# Chapter 3: Human Activities Affect Water Quality

Ensuring that water quality in aquatic environments remains within natural ranges is essential for maintaining viable, abundant and diverse communities of organisms. People have specific water quality requirements for drinking water, recreation, agriculture and industry, although the specific water quality requirements vary by sector. Degradation of water quality erodes the availability of water for humans and ecosystems, increasing financial costs for human users, and decreasing species diversity and abundance of resident communities. These changes in environmental quality can be associated with changes in water quality parameters such as sediment load, nutrient concentrations, temperature, dissolved oxygen levels, and pH. The addition of excessive levels of naturally occurring or synthetic compounds, such as oil and grease, pesticides, mercury and other trace metals, and non-metallic toxins (e.g., PAHs, and PCBs) can harm wildlife and people that depend on these aquatic resources.

Poor water quality can be the result of natural processes but is more often associated with human activities and is closely linked to industrial development. Although substances that can be harmful to life can have natural or human-made sources, the contribution of some human-produced chemicals to the natural environment far overshadows natural sources. During the industrial revolution of the $19^{th}$ century, contaminated surface waters resulted in serious human health problems, including typhoid and cholera outbreaks. To mitigate these problems, large urban centres began developing sewage networks and water treatment facilities. These facilities continue to be installed and expanded to accommodate increases in human population. However, the rapid growth in some urban areas, particularly in Asia and Latin America, has outpaced the ability of some governments to develop and maintain treatment facilities (FWR, 2004).

Since the 1940s, the development and production of synthetic chemicals used in industry and agriculture has had profound effects on water quality worldwide. Eutrophication of surface waters from human and agricultural wastes, and nitrification of groundwater from agricultural practices, have affected large parts of the world. Acidification of surface waters by air pollution is a relatively recent phenomenon and can threaten aquatic life and the long range transport of airborne pollutants is also a significant source of water quality degradation in some areas of the world. Further, urbanization, population growth, and increased rates of consumption have lead to increased resource extraction (e.g., mining and forestry), material processing (e.g., smelting, pulp and paper mills, assembly plants), and demands for energy (hydro-electrical impoundments and generating stations). The building of impoundments along watercourses for hydroelectric power generation and water storage, while playing an important role in meeting human needs for water, can significantly alter water quality (Table 4). Climate change, the evolution of new waterborne pathogens, and the development and use of new chemicals for industrial, agricultural, household, medical, and personal use have raised concern as they have the potential to alter both the availability and the quality of water (IPCC, 1995; WHO, 2003; Kolpin *et al*., 2002). All of these activities have costs in terms of water quality and the health and integrity of aquatic ecosystems (Meybeck, 2004).

Table 4. Relationship between human activity by economic sector and consequences of these activities to aquatic ecosystems

| **Consequence**: <br> **Sector**: | Sedimentation | Eutrophication | Thermal pollution | Dissolved oxygen | Acidification | Microbial contamination | Salinization | Trace metals contamination | Mercury | Non-metallic toxins | Pesticides | Hydrocarbons | Micronutrient depletion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agriculture | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | | | ✓ | | |
| Urban use | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | ✓ | ✓ | |
| Forestry | ✓ | ✓ | ✓ | | | | | | | | ✓ | | |
| Hydroelectric power generation and water storage | ✓ | ✓ | ✓ | ✓ | | | | | ✓ | | | | ✓ |
| Mining | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | | ✓ | | | |
| Industries | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | |

The development of integrated water resource management (IWRM) approaches to regulate over-exploitation of water holds promise for helping to prevent and/or reverse the degradation of water resources in many countries. Improved scientific understanding of the interaction between hydrological, chemical and biological processes within aquatic ecosystems can be used to design and implement ecohydrological solutions to water use, treatment, and extraction issues.

Ecohydrology is a scientific concept applied to environmental problem-solving. It maintains that through the manipulation of biotic and hydrological interactions in a landscape, augmenting ecosystem resilience to anthropogenic changes can be achieved. Ecohydrology quantifies and explains the relationships between hydrological processes and biotic dynamics at a catchment scale. The concept is based on the assumption that sustainable development of water resources depends on the ability to restore and maintain evolutionarily established processes of water and nutrient cycles and energy flows at the basin scale. This in turn depends on an in-depth understanding of a whole range of processes. However, this is not to say that hydrotechnical (engineering) solutions to environmental problems should be abandoned, but that ecohydrological measures should be harmonized with necessary hydrotechnical solutions (e.g., sewage treatment plants, levees in urbanized areas, etc.).

The following sections outline how water quality is affected by different processes and the ways in which human activities in different economic sectors influence these processes.

### *Sedimentation*

Sediment transport into aquatic systems results from almost all human land use and industrial activities, including: agriculture, forestry, urbanization, mining, and some industrial activities. Increases in sediment transport to aquatic systems are typically observed as bankside vegetation is degraded or removed, rivers are channelized to enable development closer to streambanks, and natural land cover is removed or replaced by human-built land cover (e.g., roads and buildings). The construction of impoundments also generates sediments and alters the natural sedimentation regime of many water courses: sediments tend to accumulate in reservoirs and ecosystems downstream of reservoirs are often depleted of natural sediment fluxes and riverbank scouring is increased.

The transport of sediments into surface waters has both physical and chemical consequences for water quality and aquatic ecosystem health. High turbidity can decrease the amount of available sunlight, limiting the production of algae and macrophytes. Fish habitat can be degraded as spawning gravel becomes filled with fine particles, restricting the oxygen available for buried eggs. Turbid waters may also damage fish directly by irritating or scouring their gills, or by reducing the success of visual predators. The scouring action of turbid waters may also harm some benthic macroinvertebrates (Owens *et al*., 2005).

Very fine sediment (less than 63µm) is often chemically active. Phosphorus and metals tend to be highly attracted to the ionic exchange sites associated with iron and manganese coatings that occur on small particles. The positive relationship between suspended solids and total phosphorus and lead concentrations is demonstrated in Figure 27. Many toxic organic contaminants, such as pesticides or their breakdown products, are strongly associated with silt, clay and organic carbon transported by rivers. Thus, sediments act as an agent in the process of eutrophication and toxicity in aquatic organisms (Ongley 1996; Boatman *et al*. 1999; Owens *et al*., 2005). High sediment loads in surface waters can also increase thermal pollution by increasing the absorption of light, thereby increasing water temperatures. Finally, high sediment loads can impair navigation and water retention facilities by silting in watercourses and filling in reservoirs thereby needing costly dredging or shortening their useful life (Owens *et al*., 2005). Dredging of reservoirs and lakes also has serious implications for the ecology of these systems.

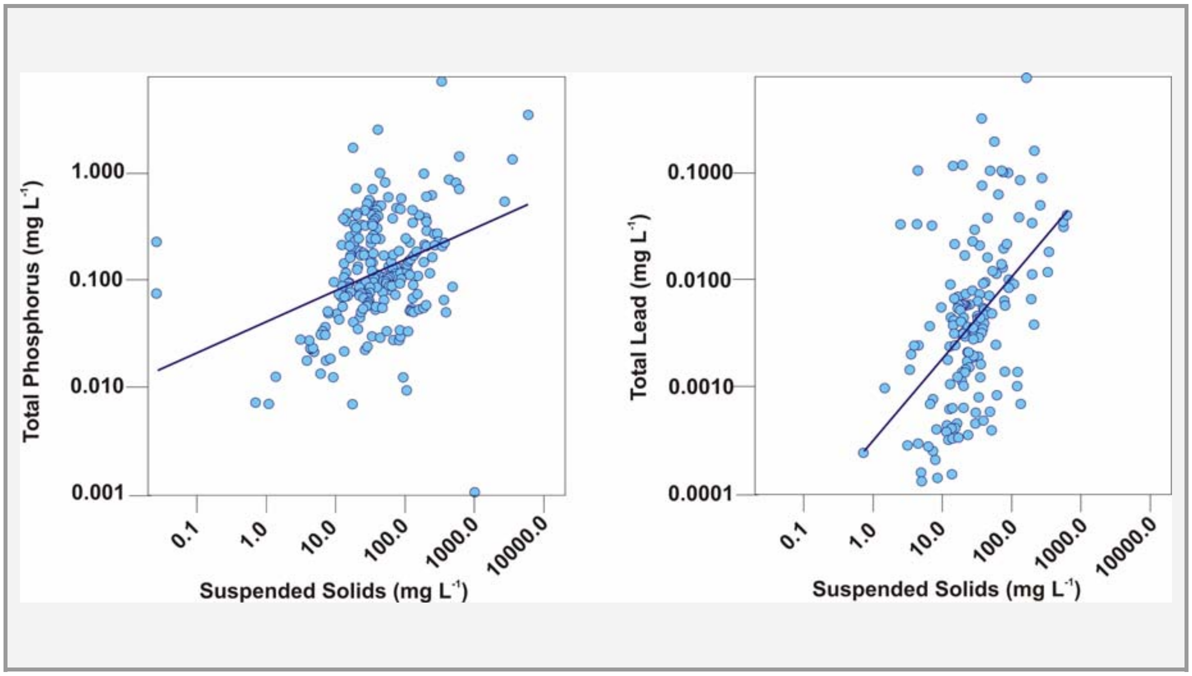
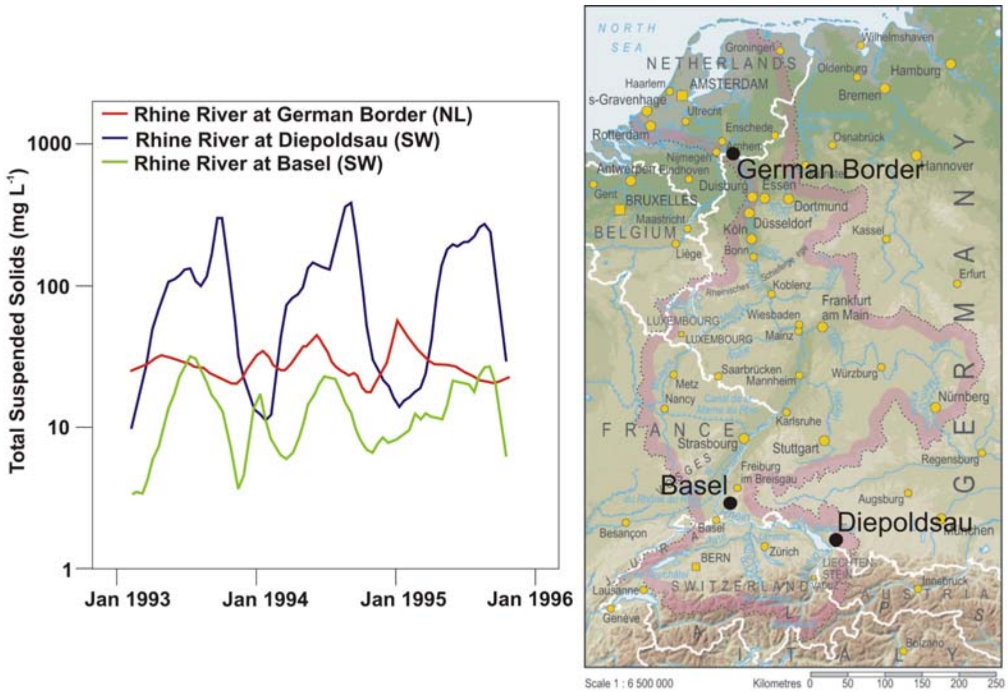



Figure 27. Relationship between total phosphorus (top panel) and total lead (bottom panel) and suspended solids concentrations at river monitoring stations. Data are station means and the solids lines show linear relationships between phosphorus and lead and suspended solids. Note that the correlation is strongest for total lead, where approximately 24% of the variability in mean lead concentrations can be explained by suspended solids (based on 157 stations). Approximately 13% of the variability in total phosphorus concentrations is explained by suspended solids (based on 225 stations).

Sediment transport through river environments may also be reduced and/or seasonal fluxes may be dampened by the construction of impoundments, such that water discharged downstream of dams and levees may be impoverished of sediment relative to natural states. Changes in suspended solids concentrations along the Rhine River, a system that is heavily managed by a series of impoundments along its length, are depicted in Figure 28. Since sediments often carry a variety of minerals, nutrients, and organic matter, this can lead to the degradation of an ecosystem by, in essence, starving it of the elements needed to sustain production (Owens *et al*., 2005).




| Station | Average River Width (m) | Average Discharge ($m^3 s^{-1}$) | Upstream Basin Area ($km^2$) |
|---|---|---|---|
| Rhine River at Diepoldsau (Switzerland) | 74 | 230 | 6,119 |
| Rhine River at Basel (Switzerland) | 211 | 1,067 | 36,472 |
| Rhine River at German Border (Netherlands) | 340 | 2,200 | 210,000 |

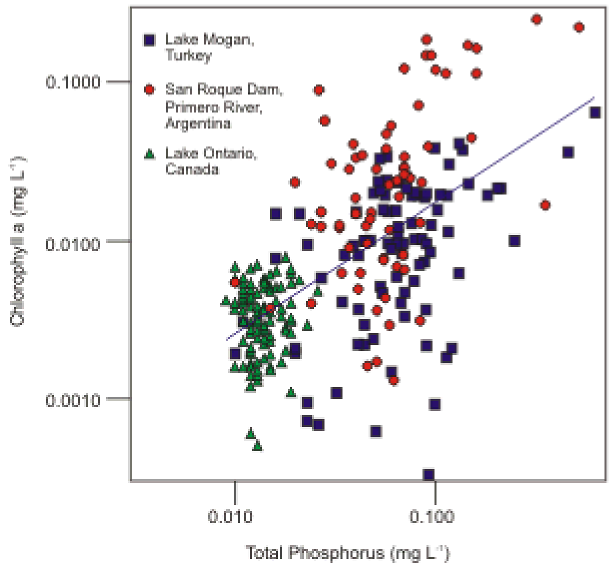
Figure 28. Total suspended solids in the Rhine River near its headwaters in Switzerland at the base of the Swiss Alps (Diepoldsau), on the German-Swiss border near Basel and downstream of Lake Constance, and at the German-Dutch border at the start of the Rhine River delta in the Netherlands. The table shows the characteristics of the river at each sampling point. Note that suspended sediment concentrations are highest and most variable at the most upstream station, where discharge patterns are likely to be erratic and dominated by snowmelt in the Alps. In contrast, suspended sediment concentrations are greatly reduced immediately downstream of Lake Constance, but variability in concentrations remains high. Suspended sediment concentrations are slightly higher at the most downstream point of the river, but much less variable, probably due to the regulatory effect of the 21 impoundments located upstream of this station, as well as numerous weirs and other flow control structures along the length of the river.

Management of sediment delivery and transport through aquatic systems has traditionally been separated into issues related to sediment quality and quantity. Sediment quality guidelines have been developed to control the release of toxic sediments into aquatic ecosystems, but implementing the guidelines is usually difficult because of very limited monitoring of sediments and lack of enforcement when guidelines are exceeded. The control of both sediment quantity and quality needs to be an integrated management scheme operating at the scale of the river basin, and taking into account the multiple environments as well as the multiple human uses. As such, it is sometimes possible to control downstream sedimentation and erosion issues by regulating activities within a basin's headwaters, but the costs of such regulations need to be considered in balance with the benefits that may be obtained further downstream (Owens *et al*., 2005).

Despite the recognition that integrated sediment management is the best solution for controlling sedimentation issues, it is practically never implemented (Owens *et al*., 2005). Difficulties of such approaches are compounded when rivers cross geopolitical borders.

### *Eutrophication*

Causes of nutrient loading, or eutrophication, of aquatic ecosystems can be attributed to agriculture, urbanization, forestry, impoundments, and industrial effluents. Surface and ground water may be equally affected by nutrient enrichment, as nutrient enriched water on the surface may percolate into groundwater supplies. Increased rates of primary production typical of eutrophic ecosystems is often manifest as excessive growth of algae and the depletion of oxygen (increased BOD), which can result in the death of fish and other animals. Nutrient enrichment can also increase the abundance of cyanobacteria (blue-green algae), which produce toxins. The relationship between total phosphorus and chlorophyll *a* (an indicator of algal biomass) concentrations has been well documented (e.g., Vollenweider and Kerekes, 1982), and is shown for two lakes and one reservoir in Figure 29. Eutrophication can lead to changes in the composition of aquatic fauna, particularly the disappearance of species with high oxygen requirements; thus, biodiversity of aquatic communities is often compromised in nutrient-enriched environments (Boatman *et al*., 1999).




| Station | Maximum Depth (m) | Lake Area (km$^2$) | Lake Volume (km$^3$) | Average Retention (yrs) | Watershed Area (km$^2$) |
|---|---|---|---|---|---|
| ■ Lake Mogan, Turkey | 3.5 | 6 | 0.013 | n.d. | 925 |
| ● San Roque Dam, Primero River, Argentina | 35 | 13 | 0.100 | 0.3 | 1750 |
| ▲ Lake Ontario, Canada | 244 | 18,484 | 1,636 | 6.3 | 76,456 |

Figure 29. Relationship between biomass of phytoplankton, measured as chlorophyll *a*, and total phosphorus at three lake and reservoir monitoring stations. Note that despite variability, chlorophyll *a* increases with phosphorus concentrations and that the relationship is consistent across three systems that vary greatly in physical characteristics. Approximately 40% of the variability in chlorophyll *a* is explained by this relationship. The solid line is the line of best fit.

The consequences of eutrophication for humans are bad taste and odour events in public water supplies, production of cyanobacterial toxins that can threaten animal and human health, infilling or clogging of irrigation canals with aquatic weeds, loss of recreation use due to slime, weed infestations and noxious odours, and economic losses due to the disappearance of species targeted in commercial and sport fisheries (Ongley, 1996). In addition, nitrate in drinking water has been linked to human health problems such as methaemoglobinaemia (blue-baby syndrome) (Boatman *et al*., 1999), stomach cancer and negative reproductive outcomes. High nitrate concentrations have also been linked to lower productivity in livestock. Figure 30 depicts nitrate and nitrite concentrations in five wells in Senegal; all but one well had ‘safe’ (i.e., below recommended guideline values) concentrations for drinking water.

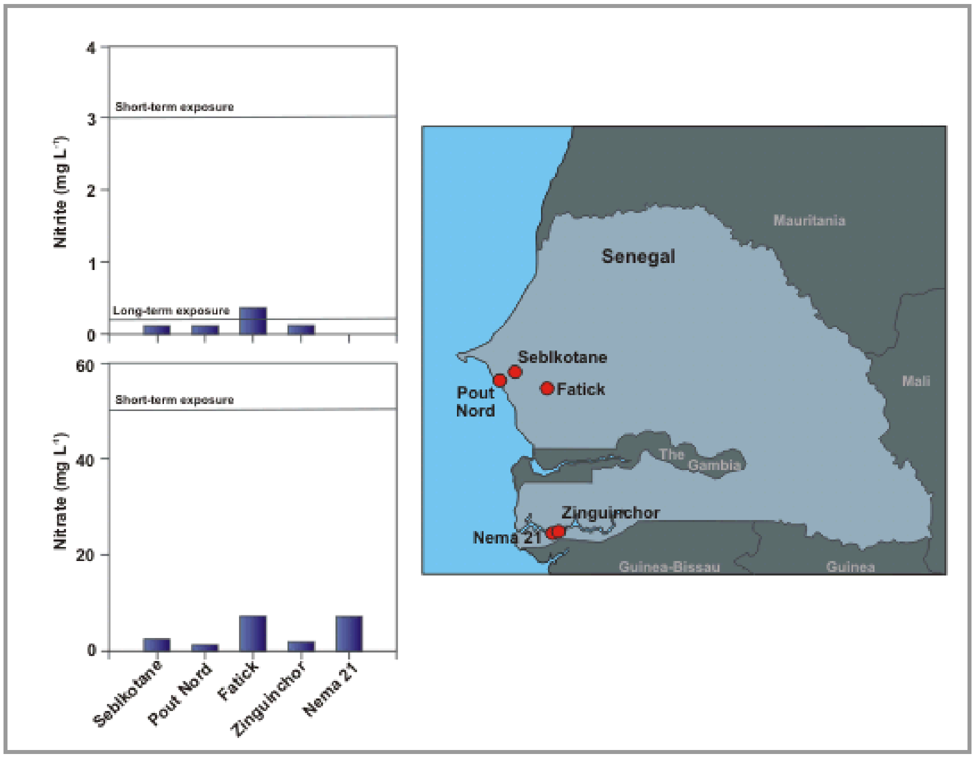



Figure 30. Nitrite (top panel) and nitrate (bottom panel) concentrations in five drilled wells in Senegal. Dashed lines indicate WHO drinking water guidelines to protect against methaemoglobinaemia in infants caused by short-term exposure to nitrate and nitrite, and a provisional guideline for long-term exposure to protect against adverse health effects in humans. Note that although none of the samples exceed short term nutrient exposure guidelines, nitrites in the Fatick well, in particular, exceeded the provisional water quality guideline.

Efforts to curb eutrophication in inland aquatic ecosystems by reducing nutrient loading rates have been underway in some parts of the world for several decades and have met with varying degrees of success when open water nutrient concentrations are examined. For example, declines in phosphorus concentrations in the Krishna River basin, in India, were not accompanied by similar declines in nitrate concentrations, whereas general declines in both nitrate and phosphorus concentrations were detected in the Vistula river basin,in Poland (Figure 31). Furthermore, nitrate concentrations in two wells in India declined following peaks in the early 1990s, as depicted in Figure 32.

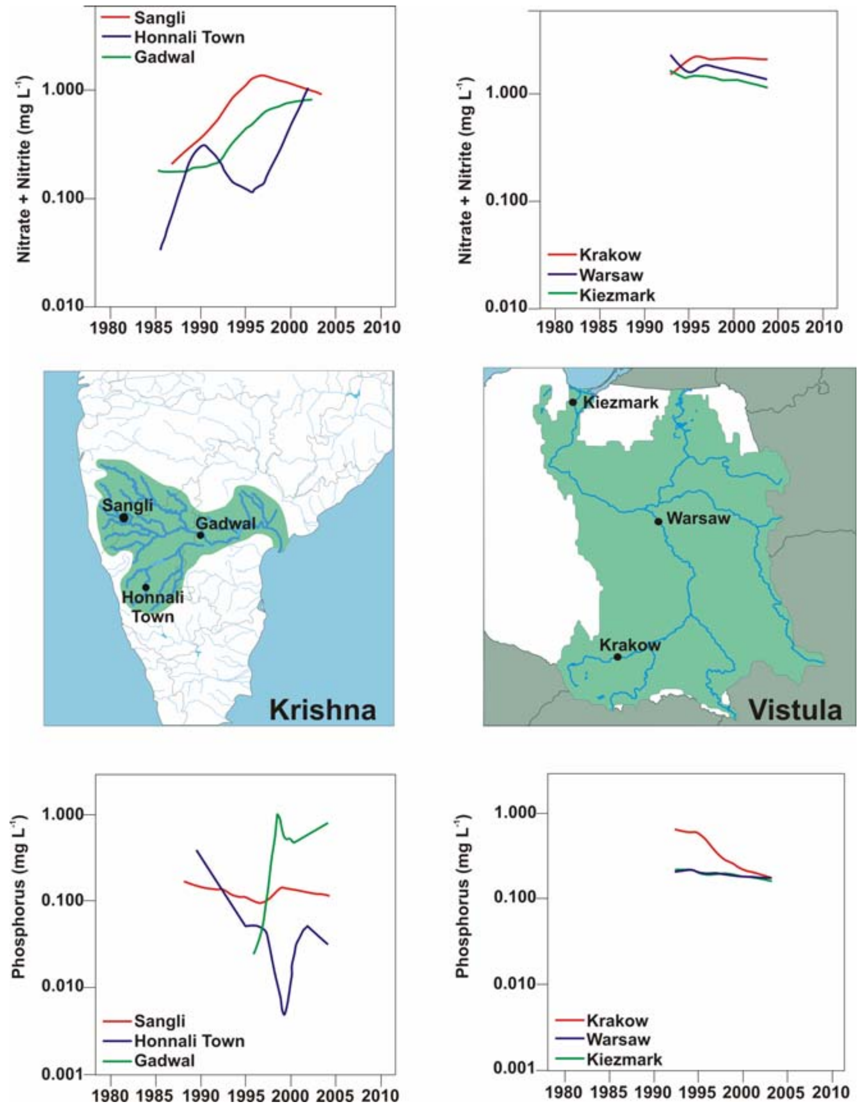



Figure 31. Nitrogen (top) and phosphorus (bottom) trends at river monitoring stations in the Krishna watershed, India, and the Vistula watershed, Poland. Lines represent locally weighted best fit lines to long-term monitoring data.

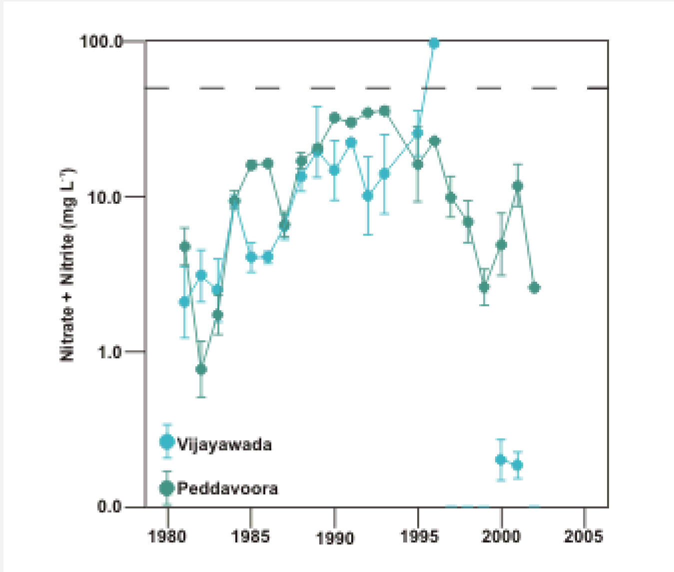



Figure 32. Combined nitrate and nitrite concentrations in two wells in India. Data shown are annual means (± 1 standard error). Note the general increase in nitrates through the 1980s and early 1990s, followed by a decline at both monitoring stations in the mid-1990s. Note also that, with the exception of the Vijayawada station in 1996, concentrations were below the WHO drinking water guideline value for protecting against methaemoglobinaemia in infants caused by short-term exposure to nitrate and nitrite.

National policy regarding nutrient management also plays a role in the degree of success achieved in mitigating eutrophication. For example, general increases in nitrate were detected in Japanese (except for one station) and Russian rivers, general decreases were detected in Swiss rivers, and slightly less than half of the Indian rivers stations reported declines in nitrate over a two decade time span (Figure 33).

As the two examples in Figures 32 and 33 demonstrate, the successful reduction of nutrient concentrations is sometimes elusive, as additional sources of nutrients constantly make their way to surface water. For instance, although cities may implement advanced wastewater treatment facilities to remove nitrogen from effluents, increased atmospheric deposition of nitrate, largely the result of automobile combustion of fossil fuels, may yield overall increased nitrogen concentrations. Similarly, stream bank fencing of animal rearing areas may reduce direct input of nutrients from manure waste, but increased fertilizer application on nearby crop fields may also yield increased nutrient concentrations during periods of runoff. Finally, increased water temperature due to climate change or thermal pollution may lead to higher levels of toxic nitrogen species, particularly in high pH waters.

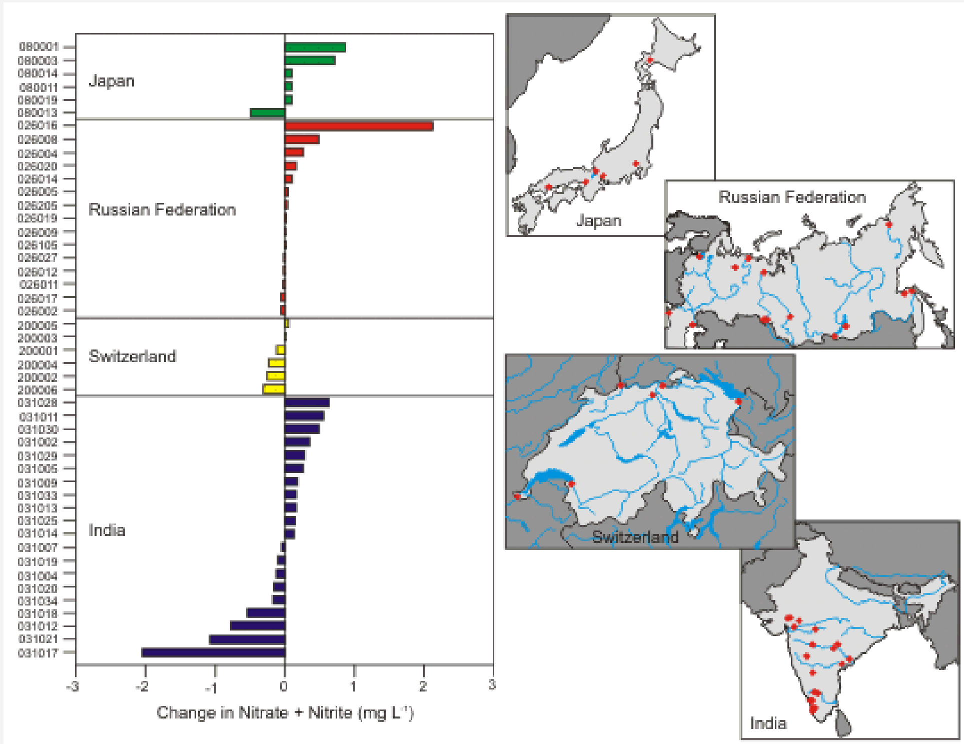



Figure 33. Change in median combined nitrate and nitrite concentrations at river monitoring stations between 1980-1984 and 2000-2004. Positive values indicate an increase and negative values indicate a decrease in combined nitrate and nitrite concentrations over time.

### *Thermal Pollution*

Urbanization, forestry, agriculture, impoundments, and industrial effluents can cause changes in surface water temperatures. Probably the most pronounced changes in temperature regimes in aquatic ecosystems can be documented downstream of coal and nuclear electrical power generating plants, where heated water is discharged into receiving environments on a continual basis. The heated water can increase local water temperatures by tens of degrees, and in temperate systems may prevent the formation of ice on a system during the winter months. Heated effluents from power generating plants often are combined with increased discharges of water to small systems that can scour native habitats and alter the physical structure of the receiving environment.

Temperature is very important to living organisms as it affects some of the basic physical and chemical processes necessary for life. For example, temperature affects the movement of molecules, fluid dynamics, and saturation concentrations of dissolved gasses in water, and the metabolic rate of organisms. Aquatic ecosystems experience diel (daily) and annual fluctuations in temperatures. This thermal regimen is crucial for aquatic fauna, as many life history traits, such as reproduction and growth, are regulated by temperature. Therefore, unseasonable changes in temperatures can eliminate species that are adapted to the natural cycle of water temperatures found in free-flowing systems. Increases in temperature will also affect the levels of dissolved oxygen in the water column, which is inversely proportional to temperature, reducing the survivorship of oxygen sensitive species (Carron and Rajaram, 2001; Hauer and Hill, 1996).

Microbial consumption of oxygen, measured as BOD, tends to increase with water temperature, and this is illustrated in Figure 34, showing the relationship between maximum BOD and maximum water temperatures at monitoring stations around the world. Higher water temperatures affect plant life by increasing growth rates, resulting in a shorter lifespan and species overabundance (i.e., algal blooms). Increases in algae and macrophyte abundance further reduce oxygen saturation in the water column. The loss of oxygen-sensitive but highly valued trophy species like trout and the aesthetic degradation caused by 'weedy' receiving waters can impact the use of the system as a recreational resource (Taylor and Helwig, 1995).

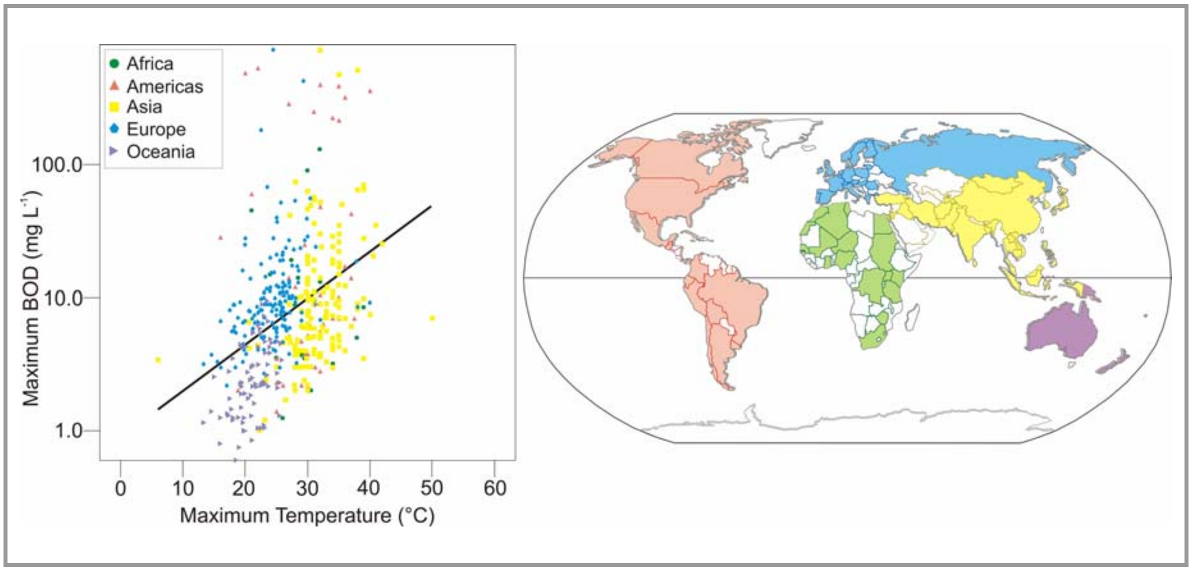



Figure 34. Relationship between maximum reported BOD and maximum reported water temperature at river monitoring stations around the world. The solid line is the 'best fit' relationship between BOD and temperature that can explain approximately 15% of the global variability in maximum BOD. Note that the high degree of uncertainty in the relationship is likely due to variability in concentrations of organic matter that may be found naturally or is released into the water from municipal and rural effluents.

Aquatic ecosystems that have received thermal effluent are able to recover from disturbance once the thermal effluent is removed. However, the degree of recovery depends on the degree of impact and the length of time the system was impacted. That is, systems that received thermal effluents with extreme temperature differences for decades can be expected to take longer to recover to natural conditions than systems that received thermal effluents for shorter periods with smaller temperature differences do (Lakly and McArthur, 2000).

### *Acidification*

Acid mine drainage, industrial effluent, and atmospheric emissions of sulphur and nitrogen oxides are largely responsible for the acidification of surface waters. Most surface waters have a pH between 6 and 8.5, and values below six can be hazardous to aquatic life. Fish, shellfish and aquatic insects have different tolerances to acidic waters and species diversity will decrease along with increased acidification. Young organisms tend to be more sensitive to acidic waters: for example, at a pH of 5, most fish eggs cannot hatch, while only some adult fish will be affected. Trophic level effects may cause indirect survivorship challenges in instances where prey species are eliminated. Acidic waters also mobilize metals that can be toxic to aquatic species (e.g., aluminium). Metal toxicity can cause reduced survivorship in fish through chronic stress, which impairs health and decreases the affected individuals' ability to secure food, shelter, or reproductive partners (Mohan and Kumar, 1998).

Industrial effluent has the potential to alter the chemistry of receiving waters and make them more susceptible to acidification. In the case of the Periyar River, India, alkalinity downstream of a rare earth metals processing plant declined significantly in the early 1980s; this decline was accompanied by an increase in the overall variability of pH. Water quality at that monitoring station also tended to have much higher hardness, conductivity, chloride, sulphate and nitrate concentrations than a baseline, upstream monitoring station, as shown in Figure 35.

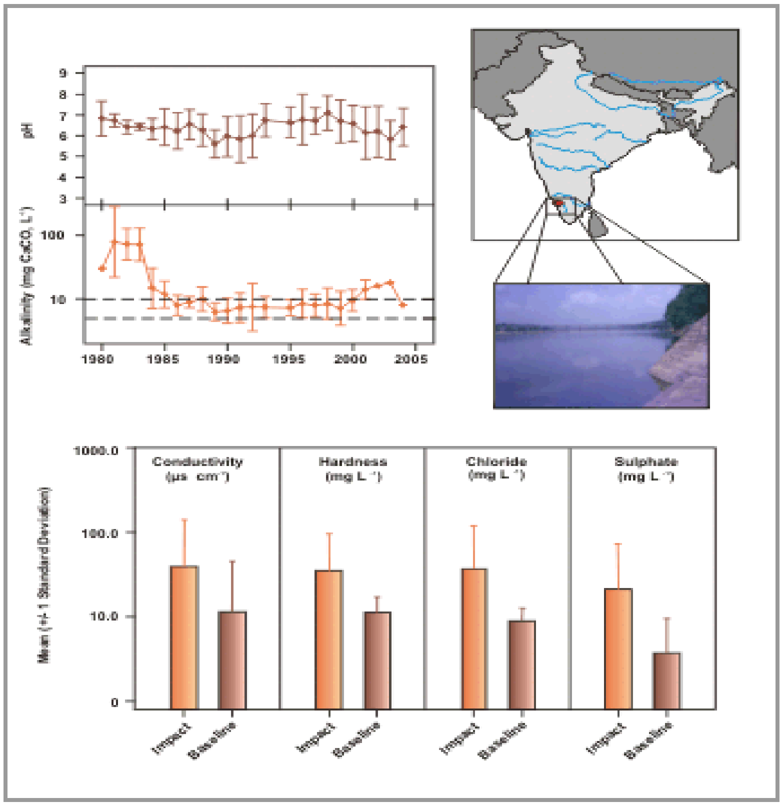



Figure 35. Top panel: Trends in annual mean (± 1 standard deviation) pH and alkalinity in the Periyar River, India, 500m downstream from a rare earth metals processing plant. Dashed lines indicate alkalinity range that is typical of systems that are highly sensitive to acidification. Bottom panel: Comparison of mean conductivity, hardness, chloride and sulphate concentrations between upstream, baseline station and downstream, impacted station in the Periyar River, India. Note that the dramatic decline in alkalinity in the mid-1980s to 'highly sensitive' status corresponds to periods where variability in mean pH concentrations increased (as shown by larger error bars around each mean). Note also that conductivity, hardness, chloride and sulphate concentrations at the impacted station, downstream of the metals processing plant, were consistently greater than the upstream, baseline station.

While acid mine drainage tends to affect individual systems and be fairly localized in its impact, industrial emissions of sulphur and nitrogen oxides to the atmosphere have affected large areas and many ecosystems. Attempts to curb acidification of terrestrial and aquatic landscapes have resulted in reduced sulphur emissions to the atmosphere in many parts of the world, but rapid development in China and India suggest these areas are at risk of acidification. Trends in pH and sulphate concentrations of surface waters from monitoring stations around the world are shown in Figure 36.

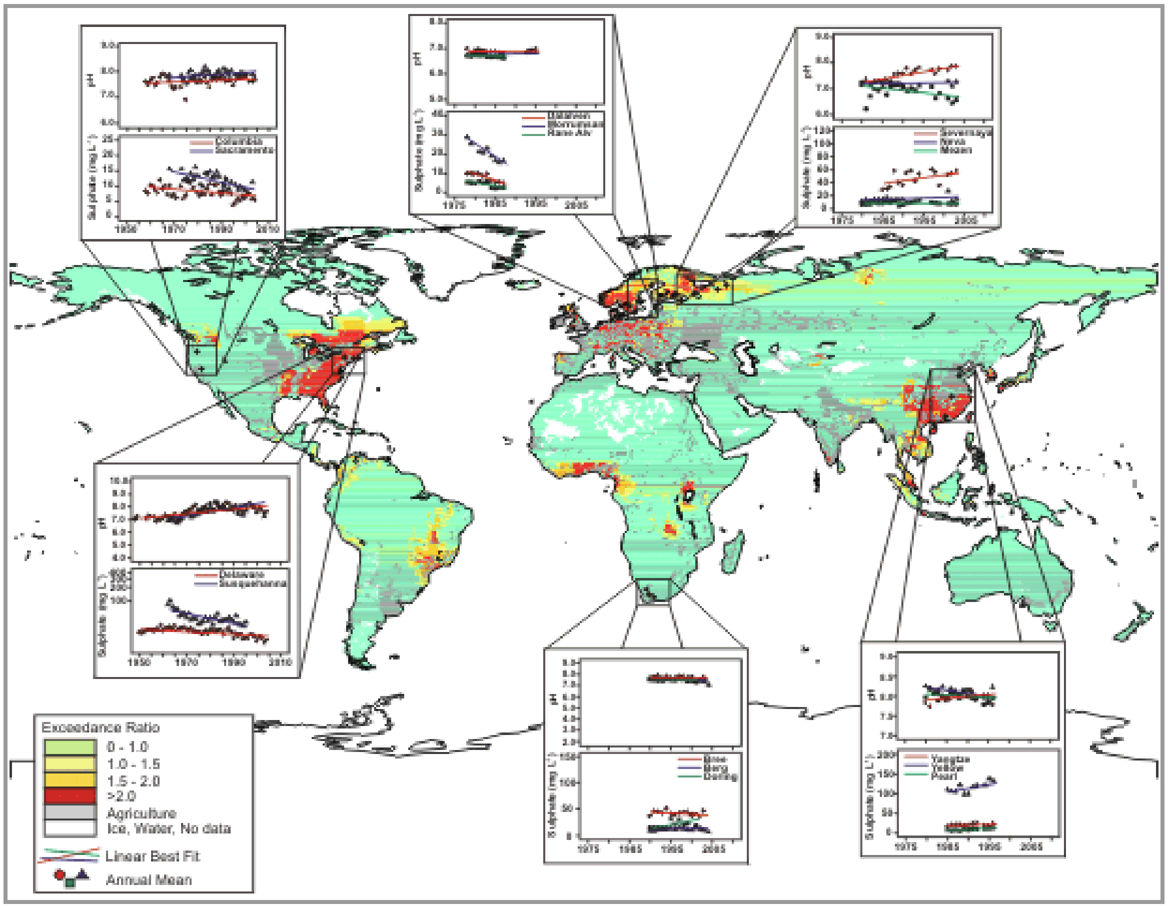



Figure 36. Trends in pH and sulphate concentrations in rivers around the world are overlayed onto a map showing sensitivity of an area to acidification. Sensitivity is measured as an exceedance ratio, which is the ratio of net acid deposition to critical load for an area, where critical load is a function of the acid buffering capacity of soils. Exceedance ratios greater than one indicate areas that are sensitive to acid deposition (Bouwman *et al*., 2002). Note the general decreases in instream sulphate concentrations in the United States and Sweden, compared to increases in China and Russia. There was very little change in pH and sulphate concentrations in South Africa, which is considered at relatively low risk of acidification based on exceedance ratios. Changes in pH do not always parallel changes in sulphate concentrations, likely due to effects of other acidifying chemicals such as nitrates.

### *Microbial Contamination*

Microbial pollution in inland waters originates primarily from agriculture and urban land uses and although contamination of a water body may occur at any time, the survival of microbial contaminants depends largely on the physical and chemical conditions of the water. Thus, microbial contamination in a water body often appears to be episodic, coinciding with periods that are favourable to microbial growth. For example, large and episodic peaks in total coliform concentrations were detected at three monitoring stations in the Ebro River, Spain over a five year sampling period in the early 1990s (Figure 37).

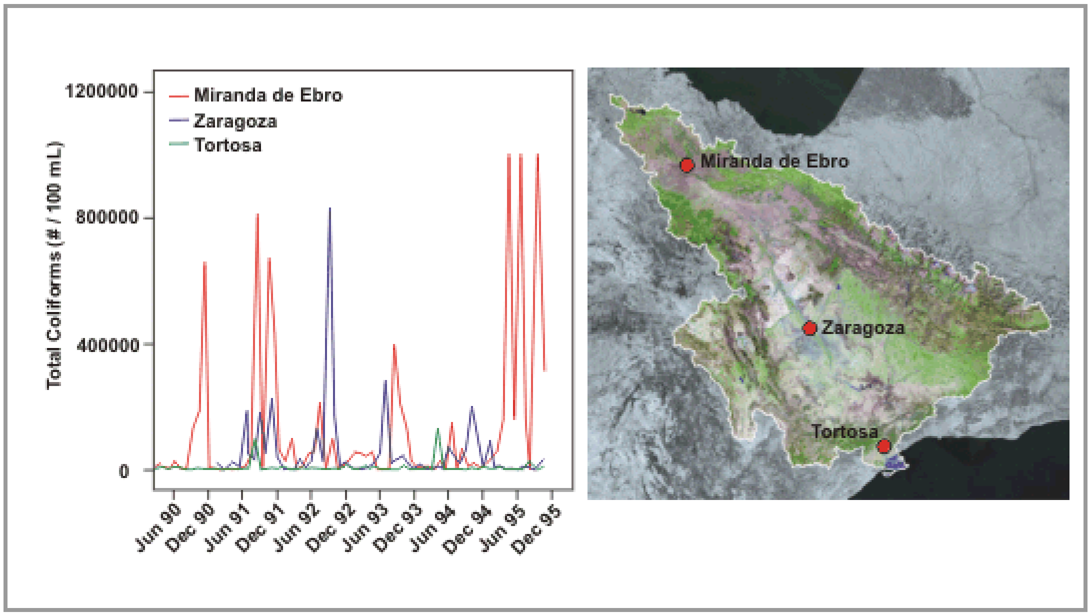



Figure 37. Total coliform concentrations at three monitoring stations in the Ebro River, Spain, measured during the early 1990s.

The largest concern about microbial pollution is the risk of illness or premature death to humans and livestock after exposure to contaminated water. Communities downstream of intensively farmed areas or municipal sewage outfalls, people working or recreating in infected waters, such as commercial or sport fishers, or agricultural workers labouring in fields treated with manure are at the highest risk of illness due to microbial pathogens. The risk of contamination increases the cost of treatment and in some instances the loss of the ecosystem resource (e.g., holiday beach tourism or shellfish harvesting). In addition, the treatment of farm waste on site can increase the cost associated with farm produce, increasing the cost of food for the average consumer (Hill, 2003).

Surface and ground water can be infected with a variety of pathogens, yet testing and monitoring for all pathogens is unrealistic, mainly because of analytical costs and technical difficulties in detecting organisms at low concentrations in chemically complex environments such as surface waters. Instead, indicator organisms are typically used to detect the presence of faecal contaminants in the water resource. In particular, either total coliforms or faecal coliforms (a subset of total coliforms) are measured as indicators of pathogenic microbes. However, testing for *Escherichia coli* (*E. coli*) alone is becoming more prominent as *E. coli* indicates the presence of only faecal contaminants, while total or faecal coliform tests may give positive results for non-faecal, naturally occurring bacterial species (Hill, 2003). In general, faecal coliform bacteria in surface waters increase with population size of cities located upstream of a sampling station, as depicted in Figure 38.

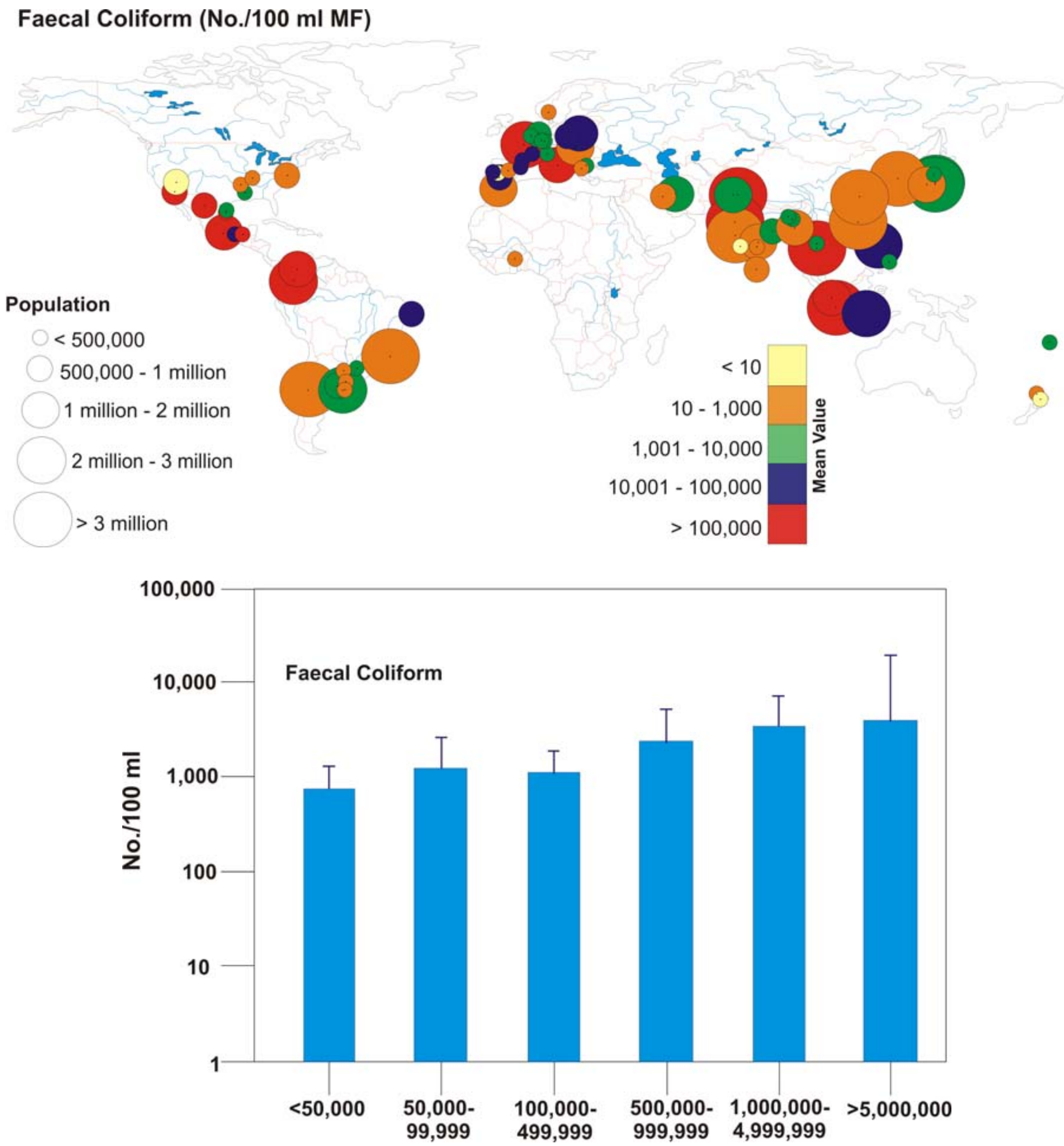



Figure 38. Faecal coliform concentrations in river monitoring stations located near to major cities, plotted according to population size (top figure). Bottom figure shows mean (± 1 standard error) faecal coliform concentrations separated by population size class of nearby cities.

Although many cities have advanced wastewater treatment facilities that effectively reduce microbial contaminant loads to near zero values, there remains a very large proportion of the world's population, primarily in developing countries, without access to improved sanitation facilities, where wastewaters are discharged directly to the environment without treatment. In fact, an estimated 2.6 billion people lacked access to improved sanitation facilities in 2002 (WHO/Unicef, 2005). The global community has a responsibility for working towards meeting the Millennium Development Goal and World Summit on Sustainable Development target (Box 1) of halving, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation. Figure 39 demonstrates that effective wastewater treatment can remove microbial contaminant loads to safe levels, indicating that proper sanitation and wastewater treatment facilities in cities and rural areas are instrumental in achieving success in meeting the MDG targets. This would result not only in improvements in human health on a global scale, but it would also indirectly result in improved ecosystem health.

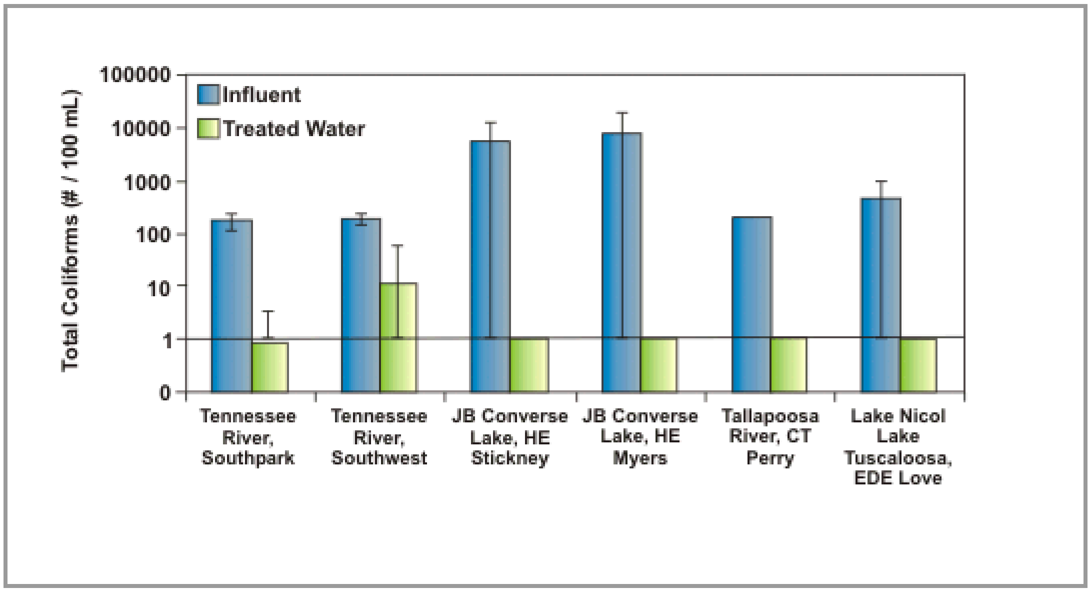



Figure 39. Total coliform concentrations in untreated, influent water and treated water at six water treatment facilities in Alabama, USA. Data are averages (± 1 standard deviation) of monthly samples collected between July 1997 and December 1998. The solid black line is the limit of analytical detection.

## *Salinization*

Anthropogenic increases in salinity and electrical conductivity in surface waters are largely due to agriculture, urbanization and industrial activities. For example, long-term monitoring of three drainage basins in South Africa show contrasting trends in electrical conductivity as a result of human activities. Conductivity in the Orange River drainage basin increased significantly between 1980 and 2004 as a result of intensive irrigation practices and varying rainfall patterns, whereas conductivity decreased significantly in the Great Fish drainage basin over the same time period as a result of interbasin transfers of water from the Orange River basin. No significant change was detected in a third drainage basin, the Tugela, over the same time period (Figure 40).

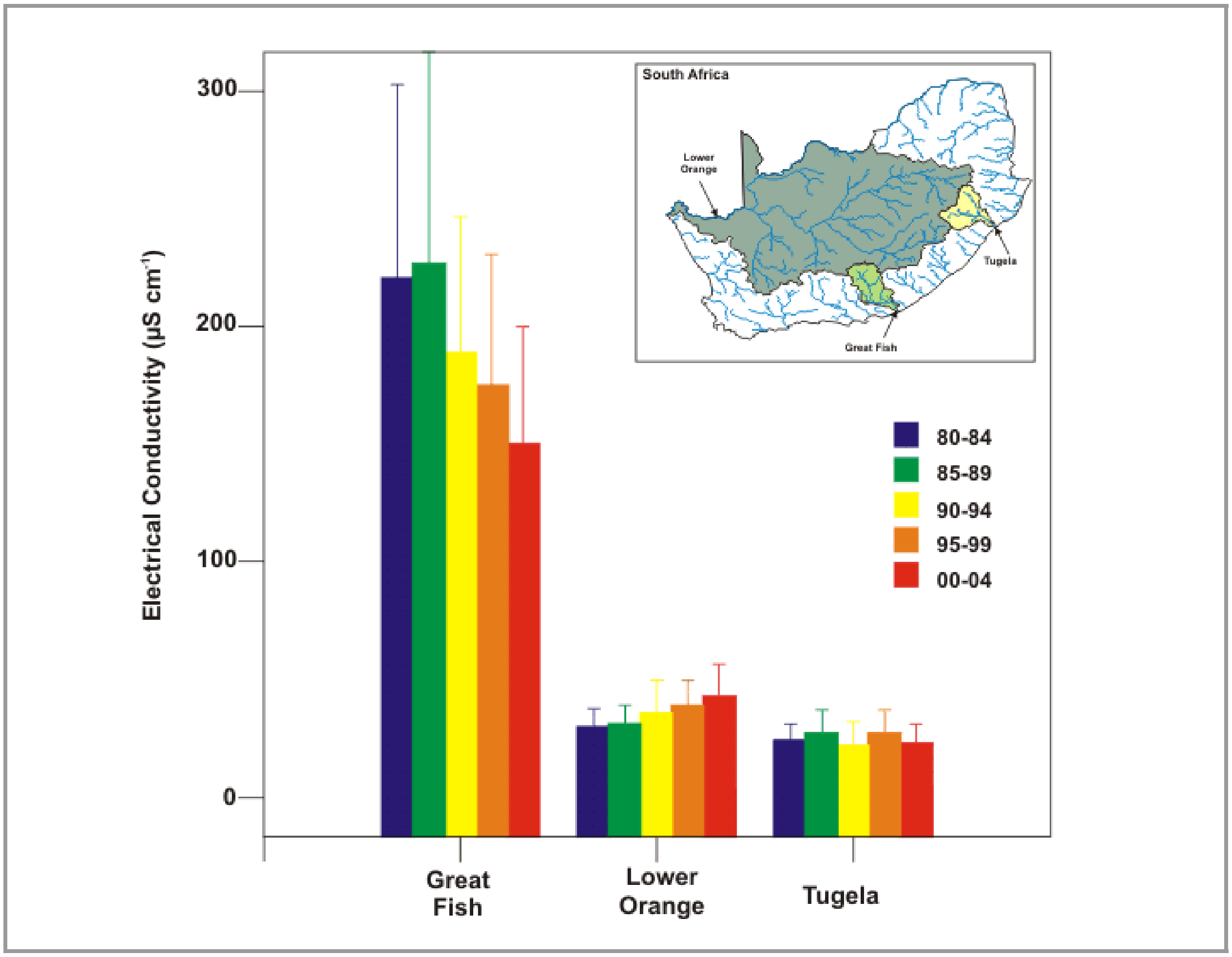



Figure 40. Electrical conductivity at three long-term river water quality monitoring stations in South Africa. Bars represent mean (± 1 standard deviation) conductivity over five-year intervals between 1980 and 2004.

Toxic conditions are created when the ionic composition and molar ratios of the receiving waters do not meet the physiological tolerance range of resident organisms. Increased salinity in aquatic ecosystems will encourage halotolerant (i.e., tolerant of saline conditions) species at the expense of halosensitive (i.e., intolerant of saline conditions) species. Saline toxicity is most often associated with high levels of ions, but there are situations in which effluents contain low levels of ions, creating de-ionized environments. The loss of biodiversity due to changes in salinity can affect invertebrates, vertebrates, aquatic plants, and riparian vegetation alike (Williams, 2001; Goodfellow *et al*., 2000).

There are economic losses associated with the diminished value of water that could otherwise be used for domestic, agricultural and industrial needs and in some instances countries incur direct costs associated with the salinization of inland waters. For example, the United States needed to build a desalinisation plant near the Colorado River to ensure international obligations for the provision of fresh (i.e., non-saline) water to Mexico were met (Williams, 2001).

### *Trace Metals and Mercury*

Elevated levels of trace metals in aquatic systems have resulted from a number of land use activities including agriculture, urbanization, impoundments, mining, and industrial activities. The effects of trace metal deposition are not always detected near the original source of contamination: long range transport of contaminants to remote areas has lead to concerns regarding trace metals (and other contaminants such as pesticides and other synthetic organic compounds) in, for example, arctic environments. Figure 41 illustrates mercury, lead and cadmium concentrations at several Arctic river monitoring stations.

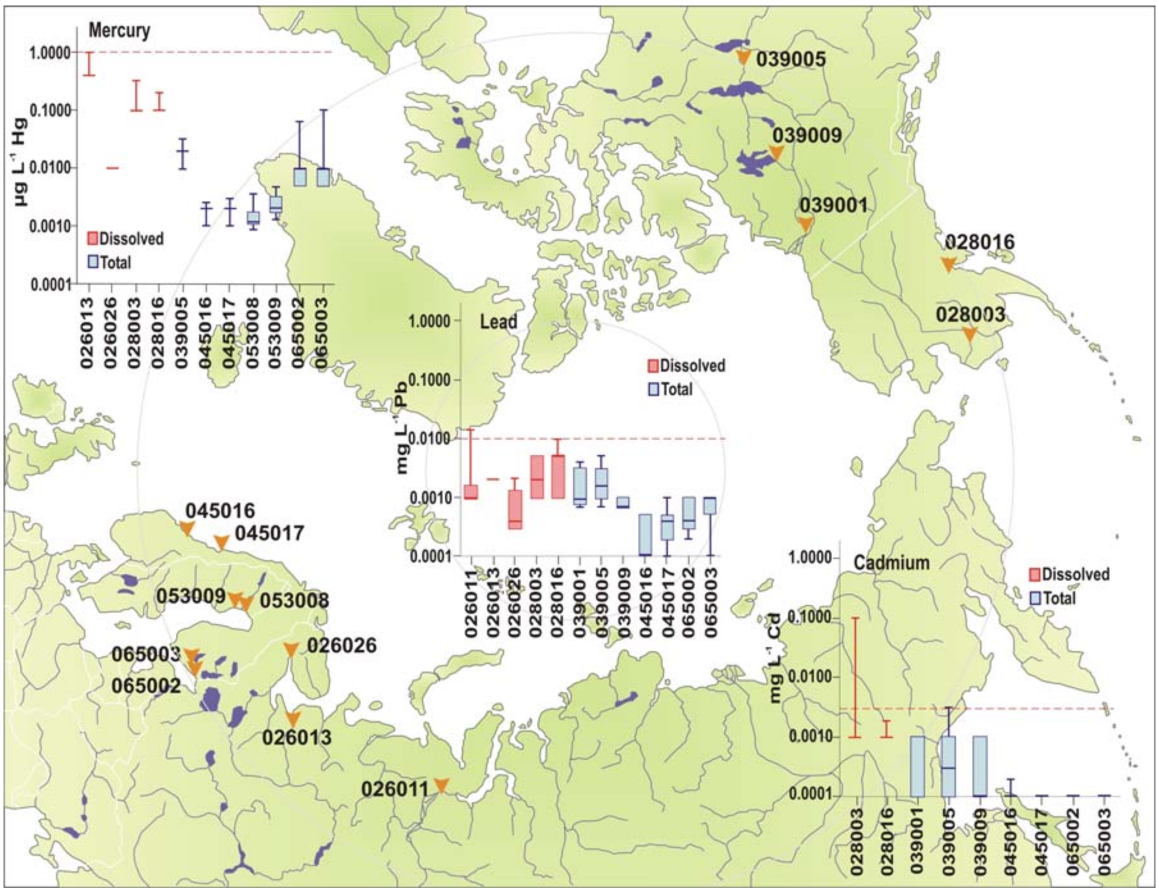



Figure 41. Concentrations of trace metals in Arctic rivers. Red lines indicate World Health Organization drinking water quality guidelines for lead, mercury and cadmium. Boxes represent median (middle line) and 25th and 75th percentile (outer limits of boxes) concentrations. 'Whiskers' represent 10th and 90th percentile concentrations at each station.

Trace metals can be harmful to aquatic organisms. Effects include reduced growth rates, impaired reproduction, and sometimes death. Acute or chronic toxicity will influence species numbers and diversity, altering community structure and function. Bioconcentration and bioaccumulation of these substances in the food chain can put terrestrial consumers, including humans, at risk. Contaminated food webs can have health and economic disadvantages for people as contaminated commercial, sport, and sustenance fisheries become restricted or closed due to high metal burdens in fish (Ongley, 1996; Driscoll *et al*., 1994; Gough and Herring, 1993; Wang, 1987).

Industrial effluents and atmospheric emissions, impoundments, and mining are also known anthropogenic sources of mercury in aquatic environments. Inorganic mercury is transformed to organic methylmercury by micro-organisms. Methylmercury is absorbed easily and bioaccumulates in exposed organisms; mercury then biomagnifies as it is transported in the food chain. Exposure to mercury can cause acute toxicity as well as neurological and reproductive problems in wildlife. Effects are more pronounced at higher trophic levels. Of particular concern are species that consume large amounts of fish such as river otters and fish eating birds. In humans, prenatal exposure to high mercury levels, particularly in fish-eating populations, has been associated with developmental problems related to the central nervous system (WHO, 2004). Loss of sustenance and commercial fisheries has been associated with high mercury concentrations in piscivorous fish species such as whitefish and northern pike (Rosenberg *et al*., 1995).

### *Pesticides*

Pesticides are frequently applied in agricultural, forestry, and urban settings. There are tens of thousands of pesticides in use, many of which are synthetically produced. Pesticides will break down in the environment forming by-products, some of which are toxic whereas others are relatively non-toxic (Baldock *et al*., 2000; Schulz, 2004). Acute (immediate) toxic effects can influence the survival or reproduction of aquatic species leading to the disruption of predator-prey relationships and a loss of biodiversity. If aquatic organisms are not harmed immediately, they may concentrate chemicals from their environment into their tissues. This bioconcentration can lead to biomagnification, a process in which the concentrations of pesticides and other chemicals are increasingly magnified in tissues and other organs as they are transferred up the food chain. The chronic effects of these substances on aquatic organisms include health repercussions such as cancers, tumours, lesions, reproductive inhibition or failure, suppressed immune systems, disruption of the endocrine (hormone) system, cellular and DNA damage, and deformities (Ongley, 1996). Terrestrial predators that feed on aquatic species may also be affected (Baldock *et al*., 2000; Mineau *et al*., 2005).

Many pesticides have been linked to health problems in humans and animals. Direct exposure can occur during the preparation and application of pesticides to crops. More frequently, exposure occurs when ingesting these agrochemicals while consuming contaminated foods. People are exposed to pesticides through aquatic systems either by ingesting fish or shellfish that have stored these compounds in their tissues or directly by drinking contaminated water. Pesticide exposure has been linked to cancer, neurological damage, immune system deficiencies, and problems with the endocrine system (Mineau *et al*., 2005; Luebke, 2002; Alavanja *et al*., 2004; Safe, 2000).

Concerns over health effects of certain compounds in humans and animals have lead to bans of certain pesticides in different parts of the world. These bans can result in noticeable improvements in surface water quality, as shown for several rivers in China in Figure 42. However, many current and historical use pesticides are capable of undergoing long-range atmospheric transport, and pesticides or their breakdown products have been detected in precipitation, surface waters, and biota in regions far from the source of their original application to the landscape (Muir *et al*., 2004; Hageman *et al*., 2006). Similar to concerns related to the long-range transport of metals and other contaminants, the deposition of pesticides in remote environments, often in Arctic and alpine regions, threatens already sensitive terrestrial and aquatic ecosystems.

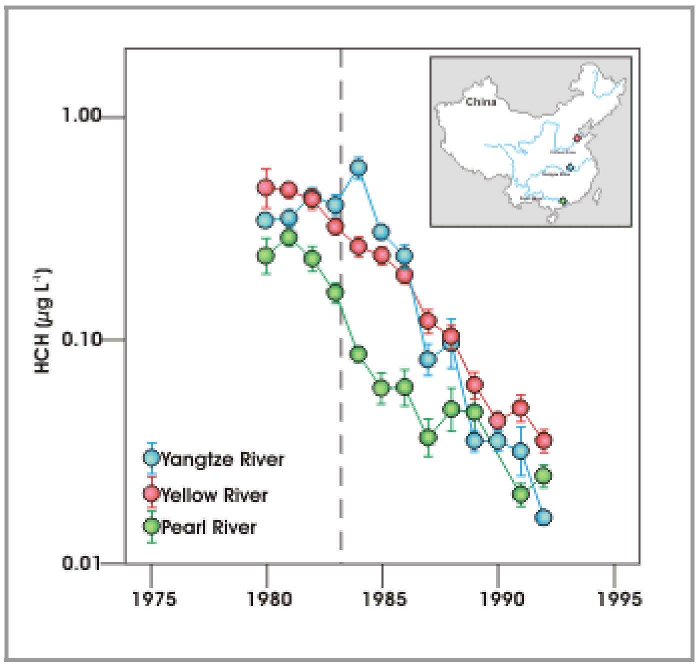



Figure 42. Mean (± 1 standard error) annual concentrations of technical hexachlorocyclohexane (HCH; also known as 'benzene hexachloride' or BHC) in three Chinese rivers between 1980 and 1993. HCH is an organochlorine insecticide that was banned from use in China in its technical form in 1983 (dashed line). HCH is composed of several isomers; the insecticide lindane is composed almost entirely of γ-HCH, and was made available in China in 1991 under restricted use (Li *et al*., 2001). Lindane is still in use in many parts of the world, and residues have been detected in surface waters.

### *Other Non-metallic Toxins*

Atmospheric emission resulting from incomplete combustion of materials during manufacturing processes, incineration of wastes or accidental fires produces toxic chemicals such as dioxins and furans and PAHs.

There are many types (hundreds to thousands) of these toxins released into the environment and they can have acute or chronic effects on the health and well-being of aquatic organisms. The effects of individual substances are diverse but include cancer, endocrine disruption, immunotoxicity, development toxicity, dermatological ailments, cardiovascular difficulties, diabetes, heritable genetic damage, neurological conditions and reproductive inhibition (DEFRA, 2004; Poster and Baker, 1995; Simoneit, 2002). These substances can be widely dispersed, either in the atmosphere or by adhering to particles carried along in rivers. They are persistent, meaning that they are resistant to decomposition, and bioaccumulate, which has lead to their classification as 'Persistent Organic Pollutants' or POPs (DEFRA, 2004).

There is a tendency to associate oil spills as the primary source of hydrocarbon contamination of aquatic ecosystems. However, only 35 percent of oil contamination of land and water originates from transportation spills (Akaishi *et al*., 2004). Much of the rest comes from industrial effluents and as a result of urban runoff (Coleman *et al*., 2002).

# Chapter 4: Emerging Threats to Water Quality

Human-caused threats to water quality such as eutrophication, acidification, and sedimentation of surface waters have been recognized for quite some time and researchers and policy makers have made considerable investments in understanding and mitigating impacts of human activities in some parts of the world. However, mitigation strategies are far from universal and often only touch on one aspect of the problem. As shown above, many effects are cumulative in nature: that is, multiple sectors of human society can affect water quality and the compounding of effects on systems can lead to catastrophic changes.

Not only have many of the ongoing problems associated with water quality not been solved, the world is also faced with new environmental problems that threaten aquatic and terrestrial ecosystems. Climate change, the decommissioning and removal of dams from waterways, the discharge of newer and more chemicals into surface waters, the identification of new and emerging pathogens, and the introduction of non-native or invasive species to aquatic ecosystems all pose challenges to scientists and governments interested in protecting the safety and health of aquatic ecosystems.

### *Climate Change and Variability*

The Earth's surface temperature has risen by about 0.6°C (± 0.2°C) on average over the past century, much of which has occurred during the past two decades. There is increasing evidence that most of the warming over the last 50 years is attributable to human activities. The chemical composition of the atmosphere is being altered through the accumulation of anthropogenically-derived sources of greenhouse gases, primarily carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide (dinitrogen oxide - $N_2O$). Although the heat-trapping property of these gases is undisputed, there is uncertainty regarding exactly how the Earth's climate responds to them and whether these are, in fact, part of the cause of increases in surface temperatures around the globe.

Changes in average temperature, precipitation levels, and rising sea level are expected to occur over the next few decades, partially in response to changes in large scale atmospheric circulation indices such as the El Niño Southern Oscillation and the North Atlantic Oscillation (Blenckner, 2005). Precipitation is expected to increase at higher latitudes and decrease at lower latitudes. An increase in ambient temperature and changes in the frequency and duration of precipitation is expected to change the intensity, frequency and duration of flood and drought events. Inland waters will be influenced by these changes through altered water temperatures, flow regimes, and water levels (IPCC, 1995). In fact, long-term monitoring records from the surface waters of lakes from around the world show marked increases in temperature in many lakes and reservoirs over the last three decades in Africa, the Americas, Europe, and Asia (Figure 43).

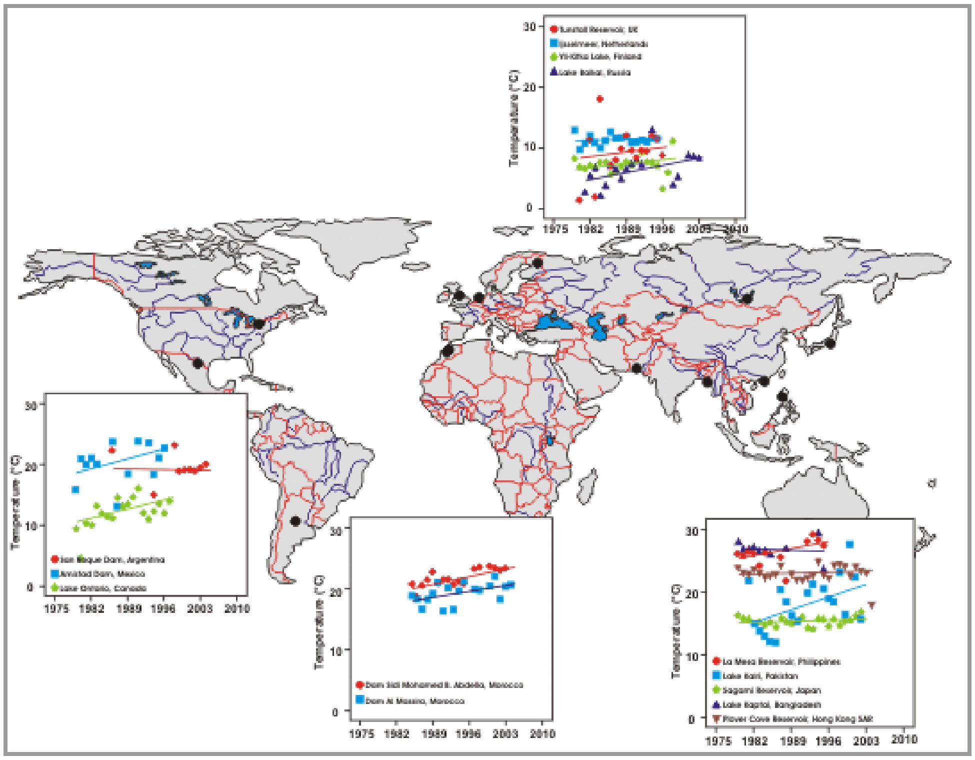



Figure 43. Mean annual surface water lake temperatures over time for long-term monitoring stations in Europe (top left), Asia (top right), Africa (bottom left), and the Americas (bottom right). Lines are 'best fit' linear regressions.

Water quality could be affected in a number of ways and some effects may be beneficial whereas others may be detrimental to both the aquatic ecosystem and to humans that rely upon the system for their personal and economic well-being. Increased temperatures could change the boundaries between the ranges of cool and cold-water organisms increasing the risk of extinction of sensitive species. Warmer water will decrease the saturation of dissolved oxygen, increasing the likelihood of anoxia. In addition, warmer temperature will increase the decomposition rate of organic material, increasing the BOD, further decreasing levels of oxygen in the water column (IPCC, 1995). Higher temperatures may reduce ice cover and alter stratification and water column mixing in lakes, key events that influence the nutrient balance of these systems (Jacobs *et al*., 2001). The cumulative effects of anthropogenic activities such as increased nutrient concentrations (agriculture and urbanization) coupled with warmer water temperatures (climate change) could accelerate biological productivity, increase plant biomass as well as the frequency of events such as algal blooms (IPCC, 1995; Jacobs *et al*., 2001). Changes in the chemical composition of the atmosphere are likely to result in increased ultraviolet radiation reaching the surface of many aquatic systems. Increased ultraviolet radiation can have direct impacts on aquatic biota by affecting growth and reproduction and will likely result in shifts in community composition as sensitive species are lost. (Häder *et al*., 1995).

Changes in the discharge of watercourses and timing of flow events, such as spring spates in temperate regions of the world, could decrease the survivorship of species that link life stages (e.g., reproduction) to these hydrological events. In areas with more frequent and intense precipitation, more contaminants and sediments will be flushed into lakes and rivers, degrading water quality and exacerbating non-point source pollution from agricultural and urban sources. However, in some areas, these higher flows could dilute pollutants and actually improve water quality. Further, increased flooding associated with more frequent and intense precipitation events could damage or overwhelm municipal treatment facilities, mine tailing ponds, or land-fills, increasing the risk of contamination. Areas of standing water could provide breeding grounds for insect and microbial pathogens, increasing the risk of disease. In regions that undergo periods of drought or receive lower than average annual rainfall, lower river flows will concentrate pollutants and increase salinity, as the dilution effects of watercourses will be reduced (Jacobs *et al*., 2001).

### Dam Removal

River impoundments are ubiquitous, particularly in the northern hemisphere. Nearly 80 percent of the total discharge of large rivers in the northern third of the world is affected by river regulation. Impoundments provide a number of services including hydroelectric generation, flood control, navigation, water supply, irrigation, and recreational opportunities. New impoundments continue to be built; however, some old dams are being removed if they no longer meet their original purposes (e.g., generating electricity), if they risk structural failure or have been abandoned, or if there is a desire to improve the abundance of migratory fish species (Dynesius and Nilsson, 1994). In fact, over 100 small dams have been removed in the United States (Born *et al.*, 1998) and in European countries such as Denmark and France (Bednarek 2001; Iversen *et al*., 1993). Dam removal has the potential to restore natural discharge patterns, improve connectivity, re-establish temperature regimes, and in time, reinstate the natural riverine sediment flux (Bednarek, 2001).

The consequences of dam removal for water quality are centred on sediment. The removal of an impoundment can release a large amount of sediment into downstream watercourses (Doyle *et al*., 2005). Increased sediment loads can damage spawning grounds, the roots and stems of macrophytes can be damaged through abrasion, and algae and insects can be scoured by moving silt and sand, and may be unable to attach to surfaces coated with deposited sediments. The release of large amounts of sediment is often a temporary effect and can be controlled with proper dam removal techniques.

Contaminated sediments may also prove problematic during the removal of a dam. Fine sediments deposited behind impoundments may have toxic substances such as PCBs sorbed to their surface. The release of this material into a watercourse may constitute a major hazard to downstream reaches. Additionally, super-saturation of dissolved oxygen may pose a threat to fish located immediately downstream of an impoundment during a dam removal. A rapid drawdown will cause a short-term increase in velocity and pressure of the water being discharged, increasing the risk of gas-bubble disease in fish.

Again, a well-planned and properly managed dam removal can eliminate the risk of dissolved gas super-saturation (Bednarek, 2001; Doyle *et al*., 2005; Lorang and Aggett, 2005).

### Waterborne and Water-Related Pathogens

Approximately 26 percent of all deaths worldwide result from infectious diseases caused by pathogenic micro-organisms. Over 1,400 species of micro-organisms have been identified that can impair human health. These organisms fall into broad categories that include bacteria, protozoa, parasitic worms, fungi, and viruses. Some pathogenic organisms have been recognized for years; however, some are considered new or emerging pathogens. Emerging pathogens are those that have begun infecting human populations for the first time or that have been known to cause disease but are increasing in incidence or expanding into areas where they have not previously been reported. In recent years, 175 species of infectious agent from 96 different genera have been classified as emerging waterborne pathogens (WHO, 2003).

Pathogens emerge for many reasons, including the creation of new environments conducive to their growth and development, such as deforestation, intensive livestock farming, and the building of dams and irrigation projects. Accidental releases (e.g., treatment plant overflows) or inadequate or non-existing water treatment facilities can introduce pathogens into drinking water supplies. Increased human interaction and travel, particularly transcontinental travel, has been implicated in the spread of diseases more quickly and over greater geographic distances than could be done in the past. The inappropriate use of antibiotics, anti-parasitic drugs, and insecticides can produce pathogens that are resistant to control measures. Piped water systems, water-cooled air conditioning plants and water devices such as cooling towers, evaporative condensers, hot water tanks and whirlpools have also been implicated in the spread of disease. These systems may sustain water temperatures and nutrient levels that favour pathogen growth and harbour films of microbes (biofilms) that can protect these organisms from disinfectants (Rose, 1990; WHO, 2003).

Water is an important environmental source and agent for transmission of many of these pathogens. Water-related pathogens that have emerged or re-emerged recently include *Cryptosporidium*, *Legionella*, *Escherichia coli* 0157, rotavirus, hepatitis E virus, and norovirus (formally Norwalk virus) (WHO, 2003).

### Chemical Contaminants

Post-World War II developments in the petrochemical and pharmaceutical industries have provided many new chemicals that offer improvements in industry, agriculture, and medical treatments. New compounds have also found applications as household and as personal care products. These substances enter the environment, disperse, and persist to a greater extent than initially anticipated. They can enter the environment intentionally through measured releases, for instance with pesticide application in agriculture; in permitted and unregulated releases of the by-products of industrial processes; or directly as household waste, which can contain cleansers, personal care products, pharmaceuticals, and biogenic hormones. Further, intensive agriculture makes use of feeds that contain veterinary pharmaceuticals. These agrochemicals are present in animal waste and are released into the environment accidentally through spills or damaged holding facilities or intentionally as a soil treatment (Kolpin *et al*., 2002; Fox, 2001).

Little is known about the prevalence, distribution, and ultimate fate of many of these compounds and their breakdown products. Part of the reason for this lack of knowledge is that, until recently, analytical tools that could detect these substances at levels that would be expected in the environment were not available. The potential concern from the environmental presence of these substances is the development of abnormal physiological processes and reproductive impairment in exposed humans and wildlife, increased risk of cancer, the development of antibiotic-resistant bacteria and the potential for increased toxicity when these compounds mix (Kolpin *et al*., 2002). Moreover, the presence of new chemicals in aquatic ecosystems has the potential to alter natural biogeochemical fluxes in the environment, with unknown consequences.

These substances can be broadly classified into a number of categories including endocrine disruptors, pharmaceuticals, and personal care products.

*Endocrine disruptors*: The endocrine system is the hormonally-based physiological system in wildlife and humans that regulates all biological processes in the body including the development of the brain and nervous system, the growth and function of the reproductive system as well as metabolism and blood sugar levels (Markey *et al*., 2002; US EPA, 2006). Some of the hormones that are vital to functioning of this system include estrogens (e.g., estradiol, estriol and estron), androgens (e.g., testosterone), and hormones secreted by the thyroid gland (e.g., thyroxine and triiodothyronine). Endocrine disruptors (EDs) are substances that interfere with the proper functioning of this system and can operate in a number of ways. They can mimic natural hormones causing the body to over-react to stimulus or to respond at inappropriate times, block the effects of hormones, or directly stimulate or inhibit the endocrine system causing overproduction or underproduction of hormones (US EPA, 2006).

Recent studies have shown that chemicals used in agriculture, industry, households, and for personal care are making their way into the environment and that many of them are suspected endocrine disruptors. These chemicals include PCBs, pesticides, disinfectants, plastic additives, flame-retardants, and pharmaceuticals (e.g., birth control pills and epilepsy medications). Some of the effects on wildlife that have been attributed to endocrine disruptors include thinning of eggshells in birds, toxicity in embryos, inadequate parental behaviour, malformations, cancerous growths in the reproductive system, and feminization of male offspring. The effects of exposure of endocrine disruptors in humans are unclear but investigations using animals and studies from wildlife populations suggest that that there is cause for concern (Markey *et al*., 2002).

*Pharmaceuticals and Personal Care Products*: There is growing concern about the possible affects of pharmaceuticals and other personal care products (PCPs) that enter surface and ground waters. These substances originate from industry, agriculture, and medical and household activities and they include commonly used products like cosmetics, detergents, and toiletries as well as pharmaceuticals such as painkillers, tranquillizers, anti-depressants, antibiotics, birth control pills, estrogen replacement therapies, and chemotherapy agents. These substances have probably been in the environment for as long as they have been in use, but our ability to detect them used to be limited as they occur at trace levels in the environment. However, recent technological developments have produced analytical tools enabling their detection in very low concentrations (Kolpin *et al*., 2002; Reynolds, 2003; Heberer, 2002).

Pharmaceutical and other PCPs can enter the environment through municipal wastewater disposal systems. Many of these compounds are not altered by municipal treatment facilities and enter receiving surface waters as contaminants. They have been detected in waste slurries, on potato fields, and even in groundwater, having arisen from landfill leachates or as contaminants in waters that recharge aquifers. The consequences of their presence in the environment are unknown. The low exposure levels currently present are not thought to produce observable acute effects. If pharmaceuticals and other PCPs do produce negative health effects for humans and wildlife, then they will most likely be subtle and manifest as behavioural or reproductive ailments (Kolpin *et al*., 2002; Reynolds, 2003; Heberer, 2002). However, a recent study has shown that tetracycline (an antibiotic commonly used to treat bacterial infections and acne) at a concentration of as little as $5 \mu g\ L^{-1}$ can affect natural bacterial production (Verma *et al*., in press).

## *Invasive Species*

Rivers, lakes, and estuaries are among the most highly invaded ecosystems in the world and the effects of invasive species on local aquatic ecosystems can be severe (Cohen, 2002). Fish species introductions are by far the best-documented examples of invasion successes (Moyle and Marchetti, 2006). Many introductions have been intentional, with the purpose of enhancing sports and commercial fisheries or for biological control. Many unintentional introductions of fish and other aquatic organisms have also occurred, and dispersal of aquatic species in the ballast waters of transoceanic ships is believed to be responsible for the successful invasion of many species on a global scale. Increases in international trade in plants and animals, as well as changes in land use and global climate are also expected to facilitate the successful invasion of non-indigenous species to aquatic ecosystems worldwide (Byers *et al*., 2002).

A well-known example of a successful biological invasion is that of the Nile perch in Lake Victoria, in East Africa. Nile perch is an effective predator and, accompanied by stresses caused by organic pollution to Lake Victoria, is attributed with the demise of hundreds of endemic cichlid species in the lake in the 1980s. Interestingly, the species was first introduced to Lake Victoria in about 1954 but did not undergo a population explosion until the 1980s, suggesting that a time lag between initial introduction and detectable impact of invasive species can sometimes be quite long (Kaufman, 1992). Although biological invasions of aquatic ecosystems have been documented for many decades, it is only recently that researchers have begun attempting to better understand the factors that can lead to successful introduction of a species as well as the biological and ecological effects of successful invasions (Ricciardi, 2003; Moyle and Marchetti, 2006). A recent study of fish species in California suggests that the success of biological invasions is, in part, due to a) the prior history of successful establishment of a species outside its natural range, b) high physiological tolerance to factors such as temperature and pH, c) similarity of new habitat to habitat in natural range, d) high biological diversity, including both native and non-native species, of the new, host ecosystem, and e) high fecundity of the invading species (Moyle and Marchetti, 2006). Similarly, invasion history of a species can be used to estimate a species' impact on a new environment: in North America, the invasion of the zebra mussel (*Dreissena polymorpha*) had predictable impacts on benthic invertebrate communities in areas where it invaded, when compared to similar invasions of the zebra mussel in parts of Europe. Moreover, because the overall impact of an invasive species is often related to its abundance, and abundance can be related to water quality, surrogate models may be developed that estimate impact of biological invasion as a function of water quality (Ricciardi, 2003).

The management of invasive species is difficult because of problems in predicting the success of biological invasions and the impact of successful invasions on the host ecosystem. However, the successful management of biological invasions, accompanied by risk assessment and intervention where appropriate, is critical to maintaining native biodiversity and normal ecosystem function. Continued research in the field of invasive species, and interaction between conservation managers and scientists should help to minimize impacts associated with future biological invasions (Byers *et al*., 2002).

# Chapter 5: Conclusion and Outlook

The preservation of aquatic resources for ecosystem and human health and well-being is a paramount concern worldwide and it has become evident that approaches to managing aquatic resources must be undertaken within the context of ecosystem dynamics in order that their exploitation for human uses remains sustainable (Nakamura *et al*., 2006). Integrated watershed resource management (IWRM) tools are widely recognized for their ability to incorporate socioeconomic, environmental and technical dimensions of aquatic environments and their drainage basins into any management scheme. If aquatic resources are not properly managed and aquatic ecosystems deteriorate, then human health and well-being may be compromised. For example, the development of conditions that promote growth of pathogens threatens the health of individuals relying on a water source for domestic consumption, whereas the loss of native fisheries as a result of species invasion and/or degraded water quality can threaten economic livelihoods of local fishers.

It is difficult to obtain a global picture of water quality, as different nations and regions struggle with different environmental pressures and the reality of limited available resources for monitoring and for targeted programs to remediate degraded systems. In many parts of the world, point source loads of contaminants are well-controlled and pollution of aquatic systems is due now mostly to non-point source transport of contaminants across the landscape and from the atmosphere (Hirsch *et al*., 2006). However, issues surrounding protection of waterways from point source effluents remain at the forefront of water quality concerns in many other parts of the world, and particularly in developing countries.

Although some problems that affect aquatic environments, such as eutrophication, are local in nature and can be solved at a local scale, (provided sufficient financial and technical resources are made available), other problems are more regional or global and require efforts on the part of the international community to ameliorate conditions worldwide. For example, climate change and variability threaten the quality of aquatic ecosystems on a global scale, and requires international efforts to curb emissions of greenhouse gases that seem to be accelerating rates of climate change. The contamination of Arctic food webs with Persistent Organic Pollutants and trace metals as a result of long range atmospheric transport is also of global importance, as activities in temperate regions have been demonstrated to have negative impacts on aquatic and terrestrial environments in remote northern regions. The acidification of aquatic ecosystems due to sulphur and nitrate emissions to the atmosphere has long been recognized as an important global issue, and some regional successes have been recorded in terms of reversing the effects of acid precipitation on aquatic ecosystems (Skelkvåle *et al*., 2005).

Water quality monitoring for the detection of trends, impacts, and improvements is further complicated because the issues of concern and available resources are constantly changing (Hirsch *et al*., 2006). Although it is not always possible to predict new and emerging threats to aquatic ecosystems, baseline water quality monitoring must be maintained to facilitate the early detection of such threats, and water resource managers should be prepared to adapt their programs to take into account these threats. Some issues will require simply the maintenance of routine monitoring, whereas others will require focused efforts to target specific parameters and/or contaminants. As an example, South Africa has recognized the need to tailor long-term water resource monitoring programmes to address issues such as salinization, eutrophication, threats to biodiversity, and microbial contamination, in addition to an extensive national hydrological monitoring programme. Denmark's national monitoring programme, which has been ongoing since 1989, is also designed to address both local and national issues and is used to assess results of national action plans to improve the aquatic environment.

Analytical techniques are constantly improving, making it possible to detect newer compounds and elements at lower concentrations. Although these improvements enable a better understanding of the realities of chemical contamination in aquatic ecosystems, they sometimes make it difficult to interpret trends over time, as shifting analytical detection limits may give the appearance of lowered concentrations when, in reality, newer analytical techniques have been refined to demonstrate the lower concentrations (Figure 44). However, there are data analysis techniques that facilitate the detection of such trends (Helsel, 2006). Moreover, the ability to detect new parameters may bring to the forefront the contamination of waterways by chemicals previously unknown.

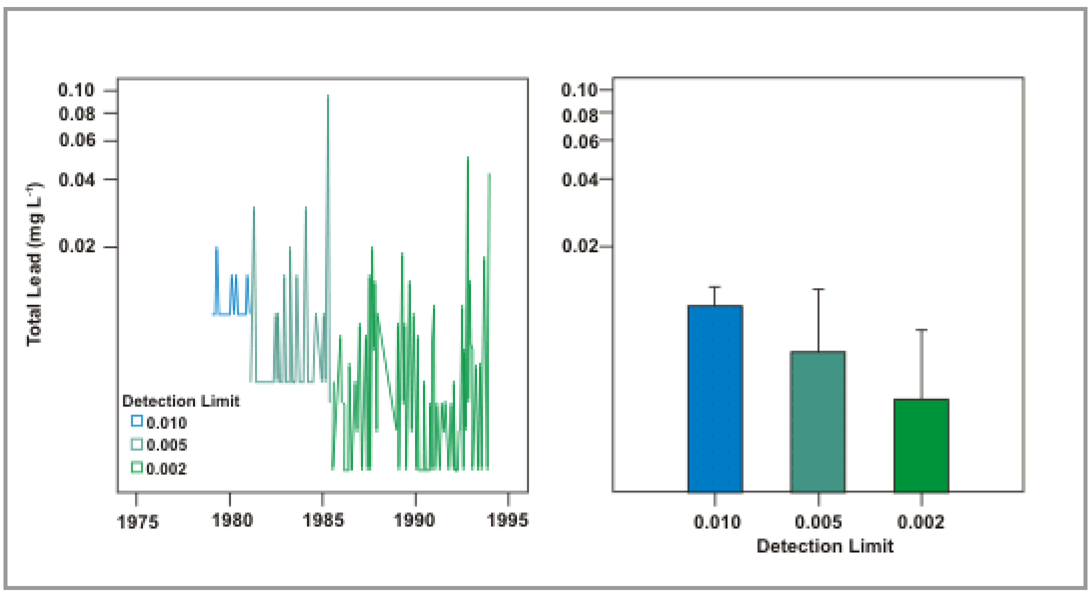



Figure 44. Example of changing analytical detection limits over time and the effects on observed mean concentrations. Data are total lead measurements from the Seine River in Paris, France, between 1979 and 1993 (left panel). Mean lead concentrations (± 1 standard deviation; right panel) of samples collected during each 'detection limit period' suggest decreasing concentrations over time, but it is difficult to conclude if the trends are real or due to improved analytical techniques and detection limits over the same period.

The difficulties involved in monitoring and management inland water resources are not insurmountable, and certainly there have been many positive examples of successful management.

Restoration of the Mesopotamian marshes in Iraq is underway, and early results show promising improvements in water quality and biodiversity (Richardson and Hussain, 2006). River restoration in Japan is extensive and many successes have been documented in systems that are heavily urbanized and located in areas of extremely high population densities (Nakamura *et al*. 2006). Nutrient abatement strategies to curb eutrophication have been successful in many parts of the world, although successes are not universal (Figure 30, Figure 32). Similarly, acidification of inland aquatic systems is not as severe as it once was (Figure 35; Skelkvåle *et al*., 2005). Although many challenges remain to properly protect aquatic ecosystem health, there is evidence that success can be achieved given sufficient planning, political and institutional will, and financial and technical resources.

The success of local, regional, and global efforts to curb rates of water quality degradation can only be measured if sufficient data are available that enable the tracking of trends over time and space. A recent survey of river restoration projects in the United States revealed that of over 37,000 projects, only 10 percent indicated that any assessment or monitoring took place as part of the projects, and that many of these activities were not designed to actually assess the outcome of the restoration efforts (Bernhardt *et al*., 2005). As such, the development of indicators that track change in response to improvement efforts is needed and forward planning into which indicators should be measured would be valuable. As was recently demonstrated in a study looking at the restoration of the Mesopotamian marshlands of Iraq, the post hoc selection of indicators to monitor change makes it difficult to assess real progress toward restoration goals (Richardson and Hussain, 2006).

The ability to enact change prior to total loss of a system depends largely on the prior information pertaining to the background conditions of the system. Hence, baseline monitoring of aquatic systems is of critical importance. Moreover, the ability to evaluate the success (or failure) of management schemes must rely on data that track a system's response to management. Such monitoring will not only provide valuable information for structuring future management projects in the form of 'lessons learned', but also it will be useful for promoting future projects by demonstrating the will to build on previous examples, and being able to clearly show strengths and weaknesses of different management scenarios.

The future of water quality at local, regional, and global scales depends on investments of individuals, communities, and governments at all political levels to ensure that water resources are protected and managed in a sustainable manner. This includes not only technological solutions to water quality problems, but changes in human behaviour through education and capacity building to better preserve aquatic resources. Cooperation in watershed management activities is also required at multiple levels in terms of both political and economic structures. Local organizations interested in managing a particular body of water are more likely to be successful if they include the primary industrial, urban, and agricultural stakeholders that rely on the body of water for economic well-being. The fact that political boundaries rarely coincide with drainage basin boundaries further compounds difficulties in developing management strategies for aquatic resources: transboundary systems require political cooperation in the development and application of management schemes if any management intends to be successful.

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Figure 1: UNEP GEMS/Water Programme – Map

Figure 2: Lake Ontario Bathymetric map modified from http://www.worldlakes.org/uploads/Ontario_bathy.jpg.

Figure 3: Photos : Hume Dam - www.afrigalah.com/river.html; Murray River - http://www.wikipedia.org/wiki/River; Mouth of Murray River – http://www.theage.com.au/ffximage/2005/09/28/29MURRAY_wideweb__430x223.jpg; South Australia map modified from http://www.waterforfood.org/newsletter/images/2005June/BasinMap_small.jpg

Figure 4: Photo: Satellite Image of Lake Baikal - http://www.maths.nottingham.ac.uk/personal/pcm/baikal/b150295a.gif

Figure 6: UNEP GEMS/Water Programme – Map

Figure 8: Map of China modified from: http://users.ox.ac.uk/~wolf1016/yellow_river_flooding.htm

Figure 9: Map of Canada modified from: http://pericat.ca/stroch/perm-images/canada-images/regions.gif; Map of the Province of Saskatchewan from: National Water Research Institute, Geomatics Department, Saskatoon, Saskatchewan

Figure 11 : Photo : Al Massira Dam - www.industcards.com/hydro-morocco.htm

Figure 13 : Map of Africa modified from: http://rhodesian.server101.com/AFRICA_MAP.gif; Map of Lake Victoria modified from: http://www.african-cichlid.com/Lake%20VictoriaMap.jpg; Map of Canada modified from: http://pericat.ca/stroch/perm-images/canada-images/regions.gif; Map of the Russian Federation modified from: http://www.fifoost.org/russland/land/rus_gr_karte.gif; Map of Ireland modified from: http://homepage.eircom.net/~rachra/images/ireland.jpg; Map of Lough Neagh modified from: www.iwai.ie/nav/bann-neagh.html

Figure 14: Satellite image of Japan: www2.gol.com/users/bartraj/Japan.jpg; Photos: Lake Mashu South Ridge - http://photos1.blogger.com/blogger/5201/2941/1600/Lake%20Mashu%20and%20Nakanoshima.jpg; Lake Mashu - http://volcano.und.edu/vwdocs/volc_images/north_asia/mashu.html

Figure 16: UNEP GEMS/Water Programme – Map

Figure 17: Elbe drainage basin image from: http://www.grid.unep.ch/product/publication/freshwater_europe/elbe.php. Photos: Elbe River near Dresden - http://dept.kent.edu/esl/dresden/Elbe%20River.jpg.

Figure 18: Rhine Drainage basin image from: http://www.grid.unep.ch/product/publication/freshwater_europe/rhine.php.

Figure 19: Map of Indonesia modified from: http://www2.u-netsurf.ne.jp/~pd53618/indopop-1.html

Figure 20: Map of Spain modified from: http://www.youlearnspanish.com/images/map,jpg

Figure 21: Map of Italy modified from: http://www.big-italy-map.co.uk/large-map-of-italy-map.htm

Figure 22: Photos : Ravi River(2): http://www.livius.org/a/pakistan/ravi/hydraotes1.jpg

Figure 23: Map of Poland modified from: http://www.appliedlanguage.com/maps_of_the_world/map_of_poland.gif

Figure 24: Map of Netherlands modified from: http://www.infoplease.com/atlas/country/netherlands.html

Figure 25: Map of Mexico modified from: www.worldpress.org/maps/maps/mexico.gif; Map of North America modified from: http://www.findsiri.com/maps/images/mexico_detail.jpg

Figure 26: Map of Switzerland modified from http://www.m-w.com/cgi-bin/nytmaps.pl?switzerland_map.gif; Map of South Korea modified from: http://Landbase.hq.unu.edu/Countryreports/2002/korea2002.htm. Photos: Han River - http://www.eonet.ne.jp/~skydragon/photograph/kinen/korea/korea.htm and Aare River - http://www.myswitzerland.com/en/navpage.cfm?category=Hike4&subcat=Schweizer%20Mittelland&id=30017

Figure 28: Map of Rhine Basin from: http://www.grid.unep.ch/product/publication/freshwater_europe/rhine.php

Figure 30: Map of Senegal modified from: http://unimaps.com/senegal/mainmap.gif

Figure 31: Krishna basin map scanned image from: National Geographic Atlas of the World Revised 6th Edition 1996; Vaal basin map modified from documentation: South Africa GEMS/Water – Initial Set of Sampling Sited Identified for Use in the GEMS/Water Global Water Quality Monitoring Network 2004; Vistula basin

map modified from: http://www.earthtrends.wri.org/maps_spatial/watersheds/europe.php

Figure 33 :Map of Japan modified from: http://sunsite.tus.ac.jp/asia/japan/maps/Japan_pol96.jpg; Map of the Russian Federation modified from: http://www.fifoost.org/russland/land/rus_gr_karte.gif; Map of Switzerland modified from: http://www.m-w.com/cgi-bin/nytmaps.pl?switzerland_map.gif; Map of India modified from: http://www.gemstat.org

Figure 34: UNEP GEMS/Water Programme – Map

Figure 35: Map of India modified from: www.gemstat.org; Photo: Periyar River – http://www.kamat.com/indica/rivers/periyar.htm

Figure 36: Map of Global distribution of acidification exceedance ratio for terrestrial natural ecosystems – medium estimates modified from Bouwman *et al*. (2002)

Figure 37: Ebro drainage basin image from: http://www.grid.unep.ch/product/publication/freshwater_europe/ebro.php

Figure 38: UNEP GEMS/Water Programme – Map

Figure 40: Polar map modified from: http://www.iceaxe.tv/KIDS/art/Arctic/ArcticMapLG.jpg

Figure 41: Map of China modified from: http://users.ox.ac.uk/~wolf1016/yellow_river_flooding.htm

Figure 42: UNEP GEMS/Water Programme – Map

## Glossary

*Acidification*

The process by which chemical compounds such as ammonia, nitrogen oxides, and psulphur dioxides are converted into acid substances. Increases in inputs of acid substances to aquatic ecosystems can change pH and impair ecosystem functioning.

*Acidity*

(1) The term acid comes from the Latin term acere, which means sour - In the late 1800s, the Swedish scientist Svante Arrhenius proposed that water can dissolve many compounds by separating them into their individual ions. Arrhenius suggested that acids are compounds that contain hydrogen and can dissolve in water to release hydrogen ions into solution.
(2) A measure of how acid a solution may be. A solution with a pH of less than 7.0 is considered acidic. Solutions with a pH of less than 4.5 contain mineral acidity (due to strong inorganic acids), while a solution having a pH greater than 8.3 contains no acidity.
(3) The proton ion concentration; also the ability of a solution to react with a base.

*Aerobic*

A technical word which means in the presence of air, and often refers to metabolic processes that function in the presence of oxygen.

*Algae (Singular – Alga)*

(1) Simple single-celled, colonial, or multi-celled, mostly aquatic plants, containing chlorophyll and lacking roots, stems and leaves. Aquatic algae are microscopic plants that grow in sunlit water that contains phosphates, nitrates, and other nutrients. Algae, like all aquatic plants, add oxygen to the water and are important in the fish food chain.
(2) Photosynthetic, almost exclusively aquatic plants of a large and diverse division of the thallophytes, including seaweeds and their fresh water allies. They range in size from simple unicellular forms to giant kelps several metres long, and display varied life-cycles and physiological processes with for example different complexes of photosynthetic pigments.
(3) Nonvascular organisms capable of oxygenic photosynthesis, without sterile cells covering gametangia.

*Alkalinity*

(1) Refers to the extent to which water or soils contain soluble mineral salts. Waters with a pH greater than 7.4 are considered alkaline.
(2) The capacity of water for neutralizing an acid solution. Alkalinity of natural waters is due primarily to the presence of hydroxides, bicarbonates, carbonates and occasionally borates, silicates and phosphates. It is expressed in units of

milligrams per litre (mg/l) of $CaCO_3$ (calcium carbonate). A solution having a pH below 4.5 contains no alkalinity.
(3) Refers to quantity and kinds of compounds present in a lake that collectively shift in pH to the alkaline side of neutrality thereby providing an index to the nature of the rocks within the drainage basin and the degree to which they are weathered.
(4) Alkalinity is frequently expressed as the total quantity of base, usually in equilibrium with carbonate or bicarbonate that can be determined by titration with a strong acid.

*Anaerobic*
A technical word which means without air, and often refers to metabolic processes that function in the absence of oxygen.

*Anoxia*
A state of being in complete absence of oxygen.

*Anthropogenic*
Relating or resulting from the influence of human beings (e.g. anthropogenic degradation of the environment).

*Aquifer*
An underground layer of water-bearing permeable rock or unconsolidated materials from which groundwater can be extracted.

*Atmospheric pressure*
The pressure above any area in Earth's atmosphere that is caused by the weight of air.

*Atrazine*
An herbicide that is used globally to stop pre- and post-emergence broadleaf and grassy weeds in major crops.

*Autotrophic*
Pertaining to an organism that produces organic compounds from carbon dioxide as a carbon source, using light or the reaction of inorganic chemicals as a source of energy.

*Bacteria (Singular: Bacterium)*
(1) Microscopic one-celled organisms which live everywhere and perform a variety of functions. While decomposing organic matter in water, bacteria can greatly reduce the amount of oxygen in the water. They also can make water unsafe to drink.
(2) Microscopic unicellular organisms, typically spherical, rod-like, or spiral and threadlike in shape, often clumped into colonies. Some bacteria cause disease, while others perform an essential role in nature in the recycling of materials, for

example, decomposing organic matter into a form available for reuse by plants. Some forms of bacteria are used to stabilize organic wastes in wastewater treatment plants, oil spills, or other pollutants. Disease-causing forms of bacteria are termed "pathogenic."

(3) Some forms of bacteria harmful to man include:

a. Total Coliform Bacteria – A particular group of bacteria that are used as indicators of possible sewage pollution. They are characterized as aerobic or facultative anaerobic, gram-negative, non-spore-forming, rod-shaped bacteria which ferment lactose with gas formation within 48 hours at 3EC. In the laboratory these bacteria are defined as all the organisms that produce colonies with a golden-green metallic sheen within 24 hours when incubated at 35EC plus or minus 1.0EC on M-Endo medium (nutrient medium for bacterial growth). Their concentrations are expressed as numbers of colonies per 100 millilitre (mL) of sample.

b. Fecal Coliform Bacteria – Bacteria that are present in the intestine or feces of warm-blooded animals. They are often used as indicators of the sanitary quality of the water. In the laboratory they are defined as all the organisms that produce blue colonies within 24 hours when incubated at 44.5EC plus or minus 0.2EC on M-FC medium (nutrient medium for bacterial growth). Their concentrations are expressed as numbers of colonies per 100mL of sample.

c. Fecal Streptococcal Bacteria – Bacteria found also in the intestine of warm-blooded animals. Their presence in water is considered to verify fecal pollution. They are characterized as gram-positive, cocci bacteria which are capable of growth in brain-heart infusion broth. In the laboratory they are defined as all the organisms that produce colonies which produce red or pink colonies within 24 hours at 35EC plus or minus 1.0EC on KF-streptococcus medium (nutrient medium for bacterial growth). Their concentrations are expressed as numbers of colonies per 100mL of sample.

*Baseline*

The background or starting point from which comparisons can be made.

*Bedrock*

The native, consolidated rock under the Earth's surface. The chemical composition of bedrock will in part determine the chemical composition of the overlying soil and water.

*Benthic*

Pertaining to the lowest level of a body of water such as a river, stream or lake. Benthic organisms inhabit the benthic zone.

*Bioaccumulation*

(1) The increase in concentration of a chemical in organisms that reside in environments contaminated with low concentrations of various organic

compounds. Also used to describe the progressive increase in the amount of a chemical in an organism resulting from rates of absorption of a substance in excess of its metabolism and excretion.
(2) Bioconcentration plus the accumulation of a compound from food.

*Bioavailability*

(1) The fraction of chemical present that is available for uptake by aquatic organisms.
(2) The degree to which toxic substances or other pollutants present in the environment are available to potentially biodegradative microorganisms. Some pollutants might be "bound up" or unavailable because they are attached to clay particles or are buried by sediment. The amount of oxygen, pH, temperature, and other conditions in the water can affect availability.

*Biochemical Oxygen Demand (BOD)*

(1) A measure of the quantity of dissolved oxygen, in milligrams per litre, necessary for the decomposition of organic matter by microorganisms, such as bacteria.
(2) A measure of the amount of oxygen removed from aquatic environments by aerobic micro-organisms for their metabolic requirements. Measurement of BOD is used to determine the level of organic pollution of a stream or lake. The greater the BOD, the greater the degree of water pollution.

*Biodiversity*

(1) The variety of life and its processes. Biodiversity includes the diversity of landscapes, communities, and populations (genetic variation). Also called Biological Diversity or Biotic Diversity.
(2) Refers to the variety and variability of life, including the complex relationships among microorganisms, insects, animals, and plants that decompose waste, cycle nutrients, and create the air that we breathe. Diversity can be defined as the number of different items and their relative frequencies. For biological diversity, these items are organized at many levels, ranging from complete Ecosystems to the biochemical structures that are the molecular basis of heredity. Thus, the term encompasses different ecosystems, species, and genes. It is generally accepted that human survival is dependent upon the conservation and preservation of this diversity of life forms. Typically five levels of biodiversity are recognized:

a. Genes – Genetic diversity encompasses the variety of genetically coded characteristics of plant and animal populations;
b. Populations – Groups of individuals of a species that interbreed or interact socially in an area;
c. Species – The level at which most organisms are recognizable as distinct from all others;
d. Natural Communities – Groups of species that typically occur in recognizable units, such as redwood forests, coastal sage scrub, or oak

woodlands.  A natural community includes all the vegetation and animal life, and their interactions within that community; and,
e. Ecosystems – A collection of natural communities.  An ecosystem can be as small as a rotting log or a puddle of water, but current management efforts typically focus on larger landscape units, such as a mountain range, a river basin, or a watershed.

*Biogeochemical*
Pertaining to the field of biogeochemistry, that is, the study of the chemical, physical, geological, and biological processes and reactions that govern the composition of the natural environment.

*Biomagnification*
The process by which a substance is passed up the food chain.  A biological process wherein a contaminant's concentration increases at each level up the food chain, including humans, resulting in an especially high level of the substance at upper levels of the food chain. Thus, the availability of such contaminants, even in the seemingly insignificant parts per trillion range, often are ecologically important.

*Biomass*
The weight of all living material in a unit area at a given instant in time.

*Biomonitoring*
A method of inferring ecological condition of an area by examining the organisms that live inhabiting the area. Although biomonitoring can occur in any ecosystem, it is most often used to assess water quality of rivers, lakes, streams, and wetlands.

*Biota*
All living organisms of an ecosystem or region.

*Biotic*
Pertaining to living organisms.

*Calcareous rocks*
Rocks that contain a high proportion of calcium carbonate.

*Carbonate mineral*
A salt or mineral that contains the carbonate ion, $CO_3^{2-}$.

*Carcinogenic*
Pertaining to any substance that promotes cancer.

*Catchment*
(1) The catching or collecting of water, especially rainfall.
(2) A reservoir or other basin for catching water.

(3) The water thus caught.
(4) Surface area drained by a network of stream channels; although "watershed" is used synonymously, watershed has been defined in European literature as a line that joins the highest points of the perimeter of the catchment.
*Catchment Area*
(1) The intake area of an aquifer and all areas that contribute surface water to the intake area.
(2) The areas tributary to a lake, stream, sewer, or drain.
(3) A reservoir or basin developed for flood control or water management for livestock and/or wildlife.

*Chemical Oxygen Demand (COD)*

A water quality measure used to indirectly measure the amount of organic compounds in water. This process converts all organic matter into carbon dioxide. It is limited in that it cannot differentiate between levels of biologically active organic substances and those that are biologically inactive.

*Chlorophyll a*

(1) The green pigments of plants. There are seven known types of chlorophyll, chlorophyll *a* and Chlorophyll *b* are the two most common forms.
(2) A green photosynthetic coloring matter of plants found in chloroplasts and made up chiefly of a blue-black ester.
(3) The primary pigment of photosynthesis in cyanobacteria and eukaryotic autotrophs; often used to indicate biomass; absorbs red and blue light.
(4) A pigment in phytoplankton that can be used to measure the abundance of phytoplankton.

*Cichlids*

Fishes from the family Cichlidae, which includes approximately 2,500 species. Cichlids are a diverse group of mainly freshwater fish, some of which are important food fishes (such as *Tilapia*), whereas others are popular aquarium fish.

*Climate Change*

(1) Climate — The sum total of the meteorological elements that characterize the average and extreme conditions of the atmosphere over a long period of time at any one place or region of the Earth's surface.
Basic types of climates include:

a. Continental – The climate characteristic of land areas separated from the moderating influences of oceans by distance, direction, or mountain barriers and marked by relatively large daily and seasonal fluctuations in temperature;
b. Oceanic – The climate characteristic of land areas near oceans which contribute to the humidity and at the same time have a moderating influence on temperature and the range of temperature variation.

(2) Ultraviolet radiation passes through the Earths atmosphere and warms the planet's surface before being reflected back into space as infrared radiation. Gases

such as carbon dioxide and methane are called Greenhouse gases, which trap some of the heat from radiation in the atmosphere. The concentration of these gases has increased dramatically as a result of human activity therefore trapping more heat and thus causing global temperatures to increase and climates to change.
(3) An alteration to measured quantities (e.g., precipitation, temperature, radiation, wind and cloudiness) within the climate system that departs significantly from previous average conditions and is seen to endure, bringing about corresponding changes to ecosystems and socioeconomic activity.
(4) Climate change can be natural (e.g., ice ages were caused by changes in the distance between the Earth and the sun), or might be caused by changes people have made to the land and atmosphere (e.g., urbanization, pollution).
(5) Often called global warming, climate change refers to: 1) raising of global temperatures; 2) increasing extremes of the hydrologic (water) cycle, which result in more frequent floods and droughts; and 3) rising of sea level due to thermal expansion of the oceans salt water.
(6) This term is commonly used interchangeably with “global warming” and “the greenhouse effect”, but is a more descriptive term. Climate change refers to the build-up of man-made gases in the atmosphere that trap the suns heat, causing changes in weather patterns on a global scale. The effects include changes in rainfall patterns, sea level rise, potential droughts, habitat loss, and heat stress. The greenhouse gases of most concern are carbon dioxide, methane, and nitrous oxides. If these gases in our atmosphere double, the Earth could warm up by 1.5 to 4.5 degrees by the year 2050, with changes in global precipitation having the greatest consequences.
(7) There is an international framework on Climate Change - United Nations Framework Convention on Climate Change (UNFCCC)

*Coliform*

(1) A group of bacteria predominantly inhabiting the intestines of man or animals but also found in soil. While typically harmless themselves, coliform bacteria are commonly used as indicators of the possible presence of pathogenic organisms.
(2) A group of organisms (Colon bacilli) usually found in the colons of animals and humans; non-pathogenic microorganisms used in testing water to indicate the presence of pathogenic bacteria. The presence of coliform bacteria in water is an indicator of possible pollution by fecal material. Generally reported as colonies per 100 millilitres (mL) of sample.

*Coliform bacteria (total and faecal)*

Coliform bacteria are a collection of relatively harmless micro-organisms that live in large numbers in the intestines of man and warm- and cold-blooded animals. Both groups have been widely used as indicators of enteric (intestinal) bacterial pathogens. The total coliform group is not as specific an indicator of faecal contamination as faecal coliforms.

*Colour*

(1) One of the most immediately apparent attributes of many natural waters and one that, together with visual clarity, strongly influences human aesthetic perception and recreational use. Colour of waters is a guide to their composition, and remote sensing of water colour is increasingly being used to infer water quality, particularly suspended solids and phytoplankton concentrations.
(2)The colour of water, with water considered a translucent (i.e., not transparent) material, is commonly associated with transmitted light. However, the colour of natural waters as observed from above is that associated with the upwelling light field that results from back scattering of sunlight illuminating the water volume. In this manner, the colour of natural waters can be objectively specified using their spectral Reflectance, where the reflectance is defined as the ratio of the upwelling light to incident (downwelling) light.

*Cyanobacteria*

(1) Prokaryotic organisms without organized chloroplasts but having chlorophyll a and oxygen-evolving photosynthesis; capable of fixing nitrogen in heterocysts; occurring in lichens both as primary photobionts and as internal or external cephalodia.
(2) A large and varied group of bacteria which possess chlorophyll a and which carry out photosynthesis in the presence of light and air, producing oxygen. They were formerly regarded as algae and were called “blue-green” algae. The group is very old and is believed to have been the first oxygen-producing organisms on Earth.

*Decomposition*

The reduction of the body of a formerly living organism into simpler forms of matter.

*Delta*

Mouth of a river where it flows into an ocean, sea, desert, or lake, building outwards from sediment carried by the river and deposited as the water current is dissipated.

*Detrital matter*

Organic waste material from decomposing plants and animals.

*Diatom*

(1) Any of the microscopic unicellular or colonial algae constituting the class Bacillarieae. They have a silicified cell wall, which persists as a skeleton after death and forms kieselguhr (loose or porous diatomite).
(2) Diatoms occur abundantly in fresh and salt waters, in soil, and as fossils. They form a large part of the plankton.
(3) One celled algae with silica shell and golden brown colouring.
(4) A microscopic single celled plant of the class Bacillariophyceae, which grows in both marine and fresh water. Diatoms secrete walls of silica called frustules, in

a great variety of forms.  Frustules may accumulate in sediments in enormous numbers.

*Discharge*

(1) The volume of water (or more broadly, the volume of fluid including solid- and dissolved-phase material), that passes a given point in a given period of time. Commonly expressed as cubic feet per second, million gallons per day, gallons per minute, or cubic metres per second.
(2) The flow of surface water in a stream or the flow of groundwater from a spring, ditch, or flowing artesian well.

*Dispersal*

Process by which an organism or population maintains or expands its distribution.

*Dissolved Oxygen (DO)*

The amount of oxygen dissolved in the water.  The availability of oxygen is one of the most important indicators of the condition of a water body as DO is necessary for the life of fish and most other aquatic organisms.

*Drainage basin*

Also called “watershed”, “river basin” or “catchment”.  Refers to the land area where precipitation runs off into streams, rivers, lakes, and reservoirs. It is a land feature that can be identified by tracing a line along the highest elevations between two areas on a map, often a ridge. Large drainage basins contain thousands of smaller drainage basins.

*Drawdown*

Lowering of the water level in a human-made reservoir.

*Drought*

Refers to an extended period where water availability falls below the statistical requirements for a region. Drought is not a purely physical phenomenon, but rather, an interplay between natural water availability and human demands for water supply.

*E coli (Escherichia Coli)*

(1) A bacterial species which inhabits the intestinal tract of man and other warm-blooded animals.  Although it poses no threat to human health, its presence in drinking water does indicate the presence of other, more dangerous bacteria.

*Escherichia coli (E. coli)*

A genus of bacteria that live in the lower intestines of warm-blooded animals, including birds and mammals. They are necessary for the proper digestion of food and are part of the intestinal flora.  Its presence in ground and surface waters is a common indicator of fecal contamination.

*Estuaries*

A semi-enclosed coastal body of water that has a free connection with the open sea and within which seawater mixes with freshwater.

*Ecohydrology*

A sub-discipline of hydrology that focuses on ecological processes involved in the hydrological cycle.

*Effluent*

(1) Flowing forth or out, especially a stream flowing out of a body of water.
(2) A surface stream that flows out of a lake or a stream, a branch that flows out of a larger stream (distributary).
(3) Water Quality – Discharged wastewater such as the treated wastes from municipal sewage plants, brine wastewater from desalting operations, and coolant waters from a nuclear power plant.

*Endocrine disruptor*

Substances that cause adverse biological effects by interfering with the endocrine system and disrupting the physiological functioning of hormones.

*Epilimnion*

(1) The warm upper layer of a body of water with thermal stratification, which extends down from the surface to the thermocline, which forms the boundary between the warmer upper layers of the epilimnion and the colder waters of the lower depths, or hypolimnion. The epilimnion is less dense than the lower waters, wind-circulated, and essentially homothermous. It typically has a higher pH and dissolved oxygen concentration than the hypolimnion.

*Eutrophic*

Pertaining to water bodies that contain high nutrient concentrations and high levels of primary productivity.

*Eutrophication*

(1) The degradation of water quality due to enrichment by nutrients, primarily nitrogen (N) and phosphorus (P), which results in excessive plant (principally algae) growth and decay. When levels of N:P are about 7:1, algae will thrive. Low dissoved oxygen (DO) in the water is a common consequence.
(2) Degrees of Eutrophication typically range from Oligotrophic water (maximum transparency, minimum chlorophyll–*a*, minimum phosphorus) through Mesotrophic, Eutrophic, to Hypereutrophic water (minimum transparency, maximum chlorophyll–*a*, maximum phosphorus). Eutrophication of a lake normally contributes to its slow evolution into a bog or marsh and ultimately to dry land. Eutrophication may be accelerated by human activities and thereby speeding up the aging process.

*Evaporation*

(1) The process of liquid water becoming water vapor, including vaporization from water surfaces, land surfaces, and snow fields, but not from leaf surfaces.
(2) The physical process by which a liquid (or a solid) is transformed to the gaseous state. In hydrology, evaporation is vaporization that takes place at a temperature below the boiling point.

*Evapotranspiration (ET)*

(1) Evapotranspiration occurs through evaporation of water from the surface, evaporation from the capillary fringe of the groundwater table, and the transpiration of groundwater by plants (Phreatophytes) whose roots tap the capillary fringe of the groundwater table.
(2) The process by which plants take in water through their roots and then give it off through the leaves as a by-product of respiration; the loss of water to the atmosphere from the Earth's surface by evaporation and by transpiration through plants.
(3) The combined processes by which water is transferred from the Earth's surface to the atmosphere; evaporation of liquid or solid water plus transpiration from plants.

*Facultative bacteria*

Bacteria which are capable of switching between aerobic and anaerobic respiration, depending on the oxygen availability of the surrounding environment.

*Faecal coliforms*

(1) A group of bacteria normally present in large numbers in the intestinal tracts of humans and other warm-blooded animals. Specifically, the group includes all of the rod-shaped bacteria that are non-sporeforming, Gram-Negative, lactose-fermenting in 24 hours at 44.5EC, and which can grow with or without oxygen. In the laboratory, they are defined as all organisms that produce blue colonies with specified time frames. The presence of this type of bacteria in water, beverages, or food is usually taken to indicate that the material is contaminated with solid human waste. Bacteria included in this classification represent a subgroup of the larger group termed Coliform. Their concentrations are expressed as number of colonies per 100mL of sample.

*Fecundity*

Potential reproductive capacity of an organism or population.

*Food web*

A description of the feeding relationships between species in a biotic community, showing the transfer of energy and material from one species to another within an ecosystem.

*Flood*

Inundation by water of any land area not normally covered with water owing to a relatively rapid change of the level of the particular water body in question.

*Flow*

The movement of water. Flow is usually expressed as the rate at which water moves through a cross-sectional area. Units of flow are often expressed as cubic metres per second ($m^3 s^{-1}$).

*Fluid dynamics*

The study of fluids in motion.

*Fungi (Singular – Fungus)*

Eukaryotic organisms that digest food externally and absorb nutrient molecules into cells. Fungi are the primary decomposers of dead plant and animal matter in many ecosystems.

*Genera (Singular – Genus)*

A taxonomic grouping that contains one or more species.

*Greenhouse gases*

Gaseous components of the atmosphere that contribute to the greenhouse effect. Greenhouse gases are transparent only to some wavelengths of light. When sunlight hits the Earth, some is absorbed and re-emitted at longer wavelengths for which the greenhouse gas is opaque, hindering emission back out into space. The major natural greenhouse gases are water vapor, which causes about 36-70% of the greenhouse effect on Earth (not including clouds); carbon dioxide, which causes between 9-26%; methane, which causes 4-9%, and ozone, which causes between 3-7%.

*Groundwater*

(1) Water that flows or seeps through water-saturated soil or rock, supplying springs and wells. The upper surface of the saturate zone is called the water table.
(2) Water stored underground in rock crevices and in the pores of geologic materials that make up the Earth's crust.

*Hardness*

(1) A water-quality indication of the concentration of alkaline salts in water, mainly calcium and magnesium. If the water you use is "hard" then more soap, detergent or shampoo is necessary to raise a lather. It also produces scale in hot water pipes, heaters, boilers and other units in which the temperature of water is increased materially.
(2) A characteristic of water which describes the presence of dissolved minerals. Carbonate hardness is caused by calcium and magnesium bicarbonate; noncarbonate hardness is caused by calcium sulfate, calcium chloride, magnesium sulfate, and magnesium chloride.

(3) The following scale may assist in appraising water hardness, measured by weight of dissolved salts (in milligrams) per unit (in litres) of water:

Soft — 0–60 milligrams/litre (mg/L);
Moderately Hard — 61–120 mg/L;
Hard — 121–180 mg/L; and
Very Hard — over 180 mg/L.

*Heterotrophic*
Pertaining to an organism that requires organic substrates to get its carbon for growth and development.

*Humic acids*
One of the major components of dark brown humic substances. Humic acids are major constituents of soil organic matter humus, contributing to soil and water chemical and physical quality. Humic acids can also be found in peat, coal, many upland streams and ocean water.

*Hydrocarbon*
Any chemical compound that consists only of the elements carbon (C) and hydrogen (H). Hydrocarbons contain a carbon backbone, called a carbon skeleton, and have hydrogen atoms attached to that backbone. Most hydrocarbons are combustible.

*Hydrology*
The study of the movement, distribution, and properties of water within the atmosphere and at the Earth's surface.

*Hypereutrophic*
Pertaining to water bodies that contain extremely high nutrient concentrations and extremely high levels of primary productivity.

*Hypolimnion*
(1) The lowermost, non-circulating layer of cold water in a thermally stratified lake or reservoir that lies below the Thermocline, remains perpetually cold and is usually deficient of oxygen.

*Hypolimnion*
The bottom and most dense layer of water in a thermally-stratified lake. Typically, it is non-circulatory and remains cold throughout the year.

*Igneous rocks*
Rocks that are formed when molten rock, or magma, cools and solidifies.

*Impoundment*
Body of water created behind a dam or other barrier that obstructs, directs, or retards flow. Also called a reservoir.

*Invertebrate*

(1) An animal belonging to the Invertebrata i.e. without a backbone, such as mollusks, arthropods and coelenterates.

*Ions*

(1) An atom or molecule that carries a net charge (either positive or negative) because of an imbalance between the number of protons and the number of electrons present. If the ion has more electrons than protons, it has a negative charge and is called an anion; if it has more protons than electrons it has a positive charge and is called a cation.
(2) (Water Quality) An electrically charged atom that can be drawn from waste water during electrodialysis.

*Lake*

(1) A considerable body of inland water or an expanded part of a river.
(2) A very slow flowing body of water in a depression in the ground not in contact with the sea.

*Leachate*

The liquid produced when water percolates through any permeable material, usually containing either or both dissolved and suspended material.

*Littoral zone*

The area between the high and low water marks in a river, lake, or estuary. However, these areas are difficult to distinguish in non-tidal systems such as rivers and lakes, and so the littoral zone is more commonly referred to as the shallow portion of a body of water, where rooted and floating plants are able to grow and primary production is high. The littoral zone often acts as a nursery for small fish and provides refugia for fish and invertebrates from predators.

*Macrophyte*

A term usually used to refer to rooted or floating aquatic vascular plants.

*Macroinvertebrate*

A term usually used to refer to aquatic invertebrates including insects, crustaceans, molluscs, and worms which inhabit a river channel, pond, lake, wetland, or ocean.

*Mesotrophic*

Pertaining to water bodies with intermediate nutrient levels and intermediate levels of primary production.

*Metabolism*

The biochemical modification of chemical compounds in living organisms and cells, include the biosynthesis of complex organic molecules and their breakdown.

*Metals*

(1) Metallic materials are normally combinations of metallic elements. They have large numbers of nonlocalized electrons; that is, these electrons are not bound to particular atoms. Many properties of metals are directly attributable to these electrons. Metals are extremely good conductors of electricity and heat and are not transparent to visible light; a polished metal surface has a lustrous appearance. Metals are quite strong, yet deformable, which accounts for their extensive use in structural applications.
(2) Tend to damage living things at low concentrations and tend to accumulate in the food chain.
(3) Some of the metals commonly found in water or sediment as pollutants include lead, copper, cadmium, arsenic, silver, zinc, iron, mercury, and nickel.
(4) Heavy metals: Metallic elements with high atomic weights, e.g., mercury, chromium, cadmium, arsenic, and lead.

*Methaemoglobinaemia*

Commonly referred to as 'blue baby syndrome', methaemoglobinaemia occurs when methaemoglobin levels in the blood are elevated, limiting the blood's ability to carry sufficient oxygen to cells. High nitrite levels in the blood are usually identified as the root cause, and limiting nitrate or nitrite intake through food, drinking water, and/or drugs can treat the condition. Most commonly detected in infants and in adults that lack the enzyme to convert methaemoglobin back to haemoglobin. Signs and symptoms include a bluish tinge to skin, especially around the mouth, hands and feet.

*Methylmercury*

Methylmercury is shorthand for monomethylmercury, and is more correctly "monomethylmercuric cation". It is composed of a methyl group ($CH_3^-$) bonded to a mercury atom; its chemical formula is $CH_3Hg^+$ (sometimes written as $MeHg^+$). As a positively charged ion it readily combines with such negative ions (anions) as chloride ($Cl^-$), hydroxide ($OH^-$) and nitrate ($NO_3^-$). It also has very high affinity for sulfur, particularly the sulfhydryl (-SH) groups on the amino acid cysteine and hence in proteins containing cysteine, forming a covalent bond. Methylmercury is a widespread bioaccumulative environmental toxin.

*Microorganism (microbe)*

A microorganism or microbe is an organism that is microscopic (too small to be visible to the naked eye). Microorganisms are often described as single-celled, or unicellular organisms; however, some unicellular protists are visible to the naked eye, and some multicellular species are microscopic. The study of microorganisms is called microbiology.

*Molar ratio*

Molecular ratio of compounds in solution.

*Monitoring*

(1) Sampling and analysis of air, water, soil, wildlife, and other conditions, to determine the concentrations of contaminants.

*Multicellular*

Refers to organisms that contain more than one cell, and having differentiated cells that perform specialized functions.

*Mutagenic*

Pertaining to an agent that changes the genetic information of an organism and increases the number of mutations above the background level.

*Nematode*

A phylum of animal composed of the roundworms, most of which are parasitic, that are ubiquitous in freshwater, marine, and terrestrial environments.

*Nitrification*

Biological oxidation of ammonia with oxygen into nitrite, followed by the oxidation of these nitrites into nitrates.

*Nitrogen*

(1) (General) Chemical symbol N, the gaseous, essential element for plant growth, comprising 78 percent of the atmosphere, which is quite inert and unavailable to most plants in its natural form.

(2) One of the three primary nutrients in a complete fertilizer and the first one listed in the formulation on a fertilizer label: 10-8-6 (nitrogen, phosphorus, potassium).

(3) (Water Quality) A nutrient present in ammonia, nitrate or nitrite or elemental form in water due possibly to Non-point Source (NPS) pollution or improperly operating wastewater treatment plants.

*Non Point Source*

Pollution sources which are diffuse and do not have a single point of origin or are not introduced into a receiving stream from a specific outlet. The commonly used categories for non-point sources are; agriculture, forestry, urban, mining, construction, dams and channels, land disposal, and saltwater intrusion.

*Nutrients*

(1) An element or compound essential to life, including carbon, oxygen, nitrogen, phosphorus, and many others.

(2) Animal, vegetable, or mineral substance which sustains individual organisms and ecosystems.

(3) That portion of any element or compound in the soil that can be readily absorbed and assimilated to nourish growing plants, e.g., nitrogen, phosphorus, potassium, iron.

*Nutrient Cycle*

The cyclic conversions of nutrients from one form to another within the biological communities. A simple example of such a cycle would be the production and release of molecular oxygen ($O^2$) from water ($H_2O$) during photosynthesis by plants and the subsequent reduction of atmospheric oxygen to water by the respiratory metabolism of other biota. The cycle of nitrogen is much more complex, with the nitrogen atom undergoing several changes in oxidation state ($N_2$, $NO_3$–, R — $NH_2$, and $NH_4$+, among others) during the cycling of this element through the biological community, and into the air, water, or soil, and back.

*Nutrient Pollution*

Contamination of water resources by excessive inputs of nutrients. In surface waters, excess algal production is a major concern. Although natural sources of nutrients exist, major sources are typically Anthropogenic (caused by human activities) and include point sources such as municipal sewage-treatment plants and industrial outflows, and non-point sources such as commercial fertilizers, animal waste, and combustion emissions.

*Oligotrophic*

Pertaining to water bodies with very low nutrient levels and low levels of primary production.

*Organic carbon*

The amount of carbon bound in organic compounds.

*Organic compounds*

Any member of a large class of chemical compounds whose molecules contain carbon and hydrogen.

*Organic matter*

Refers to any material that is capable of decay or of being decomposed or is the product of decomposition, and is usually the remains of a recently living organism, and may also include still-living organisms.

*Organochloride*

An organic compound that contains at least one covalently bonded chlorine atom. Most organochlorines have significant biological activity and have been used as powerful pesticides. Many organochlorides are persistant organic pollutants.

*Overturn*

(1) The sinking of surface water and rise of bottom water in a lake or sea that results changes in density differences caused by changes in temperature that commonly occur in spring and fall.
(2) One complete cycle of top to bottom mixing of previously stratified water masses. This phenomenon may occur in the spring or fall, or after storms, and

results in uniformity of chemical and physical properties of water at all depths. Also referred to as Turnover.

*Oxidation-Reduction State*

Also known as the redox potential. Refers to the tendency of a chemical species to acquire electrons and, therefore, be reduced. Many biochemical reactions are oxidation-reduction reactions in which one compound is oxidized and another compound is reduced and the ability of an organism to carry out these reactions is dependent on the oxidation-reduction state of the environment. Redox potential affects the solubility of nutrients and, especially, metals. Oxygen strongly affects redox potential.

*Oxidant*

A chemical compound that readily gives up oxygen or a substance that gains electrons in an oxidation-reduction chemical reaction, thereby becoming reduced.

*Oxidation*

The loss of an electron by a molecule, atom, or ion.

*Parasite*

An organism that lives on or in another organism.

*Particulate matter*

Small solid particles suspended in water of organic or inorganic origin.

*Pathogen*

(1) A disease-producing agent; usually applied to a living organism. Generally, any viruses, bacteria, or fungi that cause disease.

*Pelagic*

Pertaining to the portion of a body of water that comprises the water column but does not include the benthic (bottom) or littoral (edge) zones.

*Percolation*

(1) The movement, under hydrostatic pressure, of water through the interstices of a rock or soil.
(2) The movement of water within a porous medium such as soil toward the water table without a definite channel.
(3) The entrance of a portion of the stream flow into the channel materials to contribute to ground water replenishment.
(4) Slow seepage of water through a filter. Porous material

*Personal care products*

Refers to a wide range of products used to, e.g., soften your water, boost the cleaning power of laundry detergents and other household products, skin protecting lotions, deodorants, compounds used to prevent things like shampoos and conditioners from spoiling after purchase, and increasing the protective power of sunscreens.

*Persistent Organic Pollutants (POP)*

Organic-compounds that are resistant to environmental degradation: thus, have been observed to persist in the environment. They are capable of long-range transport, bioaccumulate in human and animal tissue, and are thought to have serious consequences for the health and well-being of humans and wildlife.

*Persistent organic pollutants (POPs)*

(1) Persistent Organic Pollutants (POPs) are chemicals that remain intact in the environment for long periods, become widely distributed geographically, accumulate in the fatty tissue of living organisms and are toxic to humans and wildlife. POPs circulate globally and can cause damage wherever they travel.
(2) There is an international convention to combat POPs - Stockholm Convention of Persistent Organic Pollutants.

*Pesticide*

Any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pest. A pesticide may be a chemical substance or biological agent (such as a virus or bacteria) used against pests including insects, plant pathogens, weeds, molluscs, birds, mammals, fish, nematodes (roundworms) and microbes that compete with humans for food, destroy property, spread disease or are a nuisance.

*pH*

A measure of the acidity/alkalinity of a solution. This measure is base don a logarithmic scale from 0 (acidic) to 14 (alkaline): a pH of 7 is considered neutral.

*Phosphorus*

(1) An element that is essential to plant life but contributes to an increased trophic level (Eutrophication) of water bodies.
(2) One of the three primary nutrients in a complete fertilizer and the second one listed in the formulation on a fertilizer label: 10-8-6 (nitrogen, phosphorus, potassium).

*Photobleaching*

The break down of the coloured component of a compound by light.

*Photosynthesis*

Biochemical process in which plants, algae, some bacteria, and some protists convert the energy of sunlight to chemical energy. The chemical energy is used to drive synthetic reactions such as the formation of sugars or the fixation of nitrogen into amino acids, the building blocks for protein synthesis. Ultimately, nearly all living things depend on energy produced from photosynthesis for their nourishment, making it vital to life on Earth.

*Phytoplankton*

The autotrophic component of the plankton that drifts in the water column. The name comes from the Greek terms, phyton or "plant" and πλανκτος ("planktos"), meaning "wanderer" or "drifter" (Thurman, 1997). Most phytoplankton are too small to be individually seen with the unaided eye. However, when present in high numbers, their presence may appear as discoloration of the water (the color of which may vary with the phytoplankton present).

*Piscivorous*

Fish-eating.

*Point Source*

A stationary location or fixed facility from which pollutants are discharged or emitted. Any single identifiable source of pollution, e.g., a pipe, ditch, ship, ore pit, factory smokestack.

*Pollutant*

A substance that directly or indirectly damages humans or the environment.

*Polychlorinated biphenyls (PCBs)*

Compounds that are produced by replacing hydrogen atoms in biphenyl with chlorine. PCBs are soluble in most organic solvents, oils, and fats, are very stable and do not degrade easily, thus, considered persistent organic pollutants. They are toxic to and can damage the health and well-being wildlife and humans.

*Polycyclic Aromatic Hydrocarbons (PAHs)*

Chemical compounds that consist of fused aromatic rings and do not contain heteroatoms or carry substituents. Many of them are known or suspected carcinogens. They are formed by incomplete combustion of carbon-containing fuels such as wood, coal, diesel, fat, or tobacco.

*Precipitation*

Any form of water that falls from the sky as part of the weather to the ground. This includes snow, sleet, hail, freezing rain, and rain.

*Primary production*

The production of organic compounds from inorganic materials principally through the process of photosynthesis (though chemosynthesis also plays a role). The organisms responsible for primary production are known as primary producers or autotrophs, and form the base of the food chain.

*Protists (Protistan)*

A heterogeneous group of living things, comprising those eukaryotes that are not animals, plants, or fungi. They are usually treated as the kingdom Protista or Protoctista. The protists are either unicellular or multicellular without highly specialized tissues.

*Protozoa*

Single-celled eukaryotic (i.e., containing a nucleus) organisms that have some mobility and are heterotrophic. Grouped in the Kingdom Protista.

*Reduction*

The gain of an electron by a molecule, atom, or ion.

*Reservoir*

Refers to an artificial lake that is used to store water for various uses. They are created first by building a sturdy dam, usually out of cement, earth, rock, or a mixture of all three. Once the dam is completed, a stream is allowed to flow behind it and eventually fill it to capacity.

*Respiration*

Respiration by individual organisms is the use of $O_2$ or the production of $CO_2$ or heat by the organism. Cellular respiration is the process in which the chemical bonds of energy-rich molecules such as glucose are converted into energy usable for life processes.

*River*

(1) Surface water finding its way over land from a higher altitude to a lower altitude, all due to gravity.

(2) The water in a river doesn't all come from surface runoff. Rain falling on the land also seeps into the earth to form ground water. At a certain depth below the land surface, called the water table, the ground becomes saturated with water. If a river bank happens to cut into this saturated layer, as most rivers do, then water will seep out of the ground into the river.

(3) A natural stream of water of considerable volume, larger than a brook or creek. A river has its stages of development, youth, maturity, and old age. In its earliest stages a river system drains its basin imperfectly; as valleys are deepened, the drainage becomes more perfect, so that in maturity the total drainage area is large and the rate of erosion high. The final stage is reached when wide flats have developed and the bordering lands have been brought low.

*Runoff*

(1) A portion of precipitation seeps into the ground to replenish Earth's ground water. Most of it flows downhill as runoff. Runoff keeps rivers and lakes full of water, but it also changes the landscape by the action of erosion.

(2) That part of the precipitation, snow melt, or irrigation water that appears in uncontrolled surface streams, rivers, drains or sewers. Runoff may be classified according to speed of appearance after rainfall or melting snow as direct runoff or base runoff, and according to source as surface runoff, storm interflow, or ground-water runoff.

(3) Runoff from agricultural land can carry excess nutrients, such as nitrogen and phosphorus into streams, lakes, and ground-water supplies. These excess nutrients have the potential to degrade water quality.

*Salinity*

Refers to the dissolved salt content of a body of water. The salt content of most natural lakes, rivers, and streams is so small that these waters are termed fresh or even sweet water. The actual amount of salt in fresh water is, by definition, less than 0.05 percent. Otherwise, the water is regarded as brackish, or defined as saline if it contains 3 to 5 percent salt by volume. At well over 5 percent it is considered brine. The ocean is naturally saline at approximately 3.5 percent salt. Some inland salt lakes or seas are even saltier. The Dead Sea, for example, has a surface water salt content of around 15 percent.

*Saturation concentration*

The concentration at which a solution can no longer dissolve more of a substance.

*Sediments*

(1) Soil, sand, and minerals washed from the land into water, usually after rain. They pile up in reservoirs, rivers, and harbors, destroying fish and wildlife habitat, and clouding the water so that sunlight cannot reach aquatic plants. Careless farming, mining, and building activities will expose sediment materials, allowing them to wash off the land after rainfall.
(2) Usually applied to material in suspension in water or recently deposited from suspension. In the plural the word is applied to all kinds of deposits from the waters of streams, lakes, or seas.
(3) The particulate matter that settles to the bottom of a liquid.

*Sessile*

Sessile organisms are those which are not able to move about. They are usually permanently attached to a solid substrate of some kind, such as a rock, or the hull of a ship in the case of barnacles.

*Sewage*

Sewage is the liquid water produced by human society which typically contains washing water, laundry waste, faeces, urine and other liquid or semi-liquid wastes. It is one form of wastewater.

*Silicate minerals*

An important class of rock forming minerals, silicate minerals contain the elements silica (Si) and oxygen (O).

*Silt*

Silt particles fall between 3.9 and 62.5 μm in diameter and are larger than clay but smaller than sand. In actuality, silt is chemically distinct from clay, and unlike clay, grains of silt are roughly the same size in all dimensions, and their size ranges overlap.

*Spate*

A sudden increase in the velocity and volume of a river owing to an influx of water, generally caused by a spell of intensive rainfall or a sudden melting of snow in the upper reaches.

*Spatial trends*

Patterns detected over a geographic area or space.

*Spawning ground*

Area in lake or river bottom where female fish deposit eggs for to be fertilized.

*Species*

A basic unit of biodiversity. The traditional definition of a species is a reproductively isolated population that shares a common gene pool and a common niche. This definition defines a species reproductively, genetically, and ecologically, and is suited to organisms that reproduce sexually. Asexually reproducing organisms may be classified into species according to phylogenetic or evolutionary traits, as determined from morphological or genetic characteristics.

*Specific Conductance (Conductivity)*

A measure of the ability of a liquid to conduct an electrical current. Conductivity is affected primarily by the geology of an area but can be influenced by anthropogenic sources. Conductivity is measured in micromhos per centimetre (µmhos $cm^{-1}$) or microsiemens per centimetre (µS $cm^{-1}$). The ability of water and its solutes to conduct electricity is influences by temperature: higher temperatures will improve conductivity.

*Stream*

(1) A general term for a body of flowing water; natural water course containing water at least part of the year. In hydrology, it is generally applied to the water flowing in a natural channel as distinct from a canal.

(2) Some classifications of streams include, in relation to time:

- a. Ephemeral Streams — Streams which flow only in direct response to precipitation and whose channel is at all times above the water table.
- b. Intermittent or Seasonal Streams — Streams which flow only at certain times of the year when it receives water from springs, rainfall, or from surface sources such as melting snow.
- c. Perennial Streams — Streams which flow continuously.

And, in relation to ground water:

- a. Gaining Streams — Streams or a reach of a stream that receive water from the zone of saturation. Also referred to as an Effluent Stream.

b. Insulated Streams — Streams or a reach of a stream that neither contribute water to the zone of saturation nor receive water from it.

*Substrate*

The natural environment in which an organism lives, or the surface or medium on which an organism grows or is attached.

*Surface water*

(1) An open body of water such as a stream, lake, or reservoir.
(2) Water that remains on the Earth's surface; all waters whose surface is naturally exposed to the atmosphere, for example, rivers, lakes, reservoirs, ponds, streams, impoundments, seas, estuaries, etc., and all springs, wells, or other collectors directly influenced by surface water.
(3) A source of drinking water that originates in rivers, lakes and run-off from melting snow. It is either drawn directly from a river or captured behind dams and stored in reservoirs.

*Suspended Solids*

Total-suspended-solids refer to the dry-weight of particles trapped by a filter of a specified pore size. The TSS of a water sample is determined by pouring a carefully measured volume of water through a pre-weighed filter of a specified pore size, then weighing the filter again after drying to remove all water.

*Taxonomy*

The science of classifying organisms using, most often, a hierarchical classification scheme.

*Thermal stratification*

Separation of water into layers due to temperature gradients set up between surface and deep waters. Stratification usually leads to the formation of the epilimnion, the metalimnion, and the hypolimnion.

*Temporal trends*

Patterns detected over time.

*Thermocline*

(1) The region in a thermally stratified body of water which separates warmer oxygen-rich surface water from cold oxygen-poor deep water and in which temperature decreases rapidly with depth. Typically, the temperature decrease reaches 1ºC or more for each metre of descent (or equivalent to 0.55ºF per foot).

*Total Dissolved Solids (TDS)*

Total-dissolved-solids is that portion of solids in water that can pass through a filter of a specific pore size. This material can include carbonate, bicarbonate, chloride, sulphate, phosphate, nitrate, calcium, magnesium, sodium, organic ions, and other ions. TDS is measured by filtering a water sample then collecting the water that passes through the filter. This water is evaporated in a pre-weighed dish them weighed. The increase in weight of the dish represents the total dissolved solids.

*Toxic*

(1) Describing a material that can cause acute or chronic damage to biological tissue following physical contact or absorption.
(2) Substances that even in small quantities may poison, cause injury, or cause death when eaten or ingested through the mouth, absorbed through the skin or inhaled into the lungs.

*Toxicity*

A measure of the degree to which something is toxic, or poisonous.

*Trace metals*

Metals in extremely small quantities in animal or plant cells and tissues. The trace metals include iron, magnesium, zinc, copper, chromium, molybdenum, and selenium.

*Trophic levels*

(1) Successive stages of nourishment as represented by the links of the food chain. According to a grossly simplified scheme the primary producers (i.e., phytoplankton) constitute the first trophic level, herbivorous zooplankton the second trophic level, and carnivorous organisms the third trophic level.
(2) Referring to the hierarchy within the food chain. Because energy is lost in the form of heat at each level within the food chain and the quantity of life that can be supported becomes smaller at each level, trophic levels are usually visualized as a pyramid.

*Trophic state (eutrophic, mesotrophic, oligotrophic, hypereutrophic, hyperoligotrophic)*

(1) Trophic State Index (TSI) — A measure of Eutrophication of a body of water using a combination of measures of water transparency or turbidity (using Secchi Disk depth recordings), Chlorophyll–a concentrations, and total phosphorus levels. TSI measures range from a scale 20–80 (referred to as Carlson's Trophic State Index).
(2) Degrees of eutrophication typically range from Oligotrophic water (maximum transparency, minimum chlorophyll–*a*, minimum phosphorus) through Mesotrophic, Eutrophic, to hypereutrophic water (minimum transparency, maximum chlorophyll–*a*, maximum phosphorus).

a. Eutrophic Reservoirs and lakes which are rich in nutrients and very productive in terms of aquatic animal and plant life.
b. Mesotrophic Reservoirs and lakes which contain moderate quantities of nutrients and are moderately productive in terms of aquatic animal and plant life.

c. Oligotrophic Reservoirs and lakes which are nutrient poor and contain little aquatic plant or animal life.

*Turbidity*

(1) The amount of solid particles that are suspended in water and that cause light rays shining through the water to scatter. Thus, turbidity makes the water cloudy or even opaque in extreme cases. Turbidity is measured in nephelometric turbidity units (NTU) or Formazin turbidity units (FTU) depending on the method and equipment used. The turbidity may be caused by a wide variety of suspended materials, such as clay, silt, finely divided organic and inorganic matter, soluble colored organic compounds, plankton and other microscopic organisms and similar substances.
(2) Turbidity in water has public health implications due to the possibilities of pathogenic bacteria encased in the particles and thus escaping disinfection processes. Turbidity interferes with water treatment (filtration), and affects aquatic life. Excessive amounts of turbidity also make water aesthetically objectionable. The degree of the turbidity of water is measured by a Turbidimeter.

*Ultraoligotrophic*

Pertaining to water bodies that contain extremely low nutrient concentrations and extremely low levels of primary productivity.

*Ultraviolet radiation*

Electromagnetic radiation with a wavelength shorter than visible light (1 – 380nm).

*Urbanization*

Urbanization refers to the natural expansion of an existing human population, namely the proportion of total population or area in urban localities or areas (cities and towns), or the increase of this proportion over time. It can thus represent a level of urban population relative to total population of the area, or the rate at which the urban proportion is increasing.

*Unicellular (single-celled)*

Organisms that contain only one cell.

*Vascular plants*

Refers to plants in the Kingdom Plantae (also called Viridiplantae) that have specialized tissues for conducting water. Vascular plants include the ferns, clubmosses, horsetails, flowering plants, conifers and other gymnosperms.

*Velocity*

(1) Rate of motion of a stream measured in terms of the distance its water travels in a unit of time, usually expressed in metres or feet per second.

*Vertical gradient*

Commonly found in lakes and deep water systems, vertical gradients are set up as a result of density differences in the water where lighter, less dense water tends to float to the surface and heavier, denser water settles to the bottom. Gradients in salinity, pH, dissolved oxygen, and temperature can often be detected during relatively stable periods.

*Virus*

Refers to a submicroscopic particle that can infect the cells of a biological organism. At the most basic level viruses consist of genetic material contained within a protective protein shell called a capsid, which distinguishes them from other virus-like particles such as prions and viroids. The study of viruses is known as virology.

*Wastewater treatment*

(1) Any of the mechanical or chemical processes used to modify the quality of waste water in order to make it more compatible or acceptable to man and his environment.

a. Primary wastewater treatment--the first stage of the wastewater-treatment process where mechanical methods, such as filters and scrapers, are used to remove pollutants. Solid material in sewage also settles out in this process.

b. Secondary wastewater treatment--treatment (following primary wastewater treatment) involving the biological process of reducing suspended, colloidal, and dissolved organic matter in effluent from primary treatment systems and which generally removes 80 to 95 percent of the Biochemical Oxygen Demand (BOD) and suspended matter. Secondary wastewater treatment may be accomplished by biological or chemical-physical methods. Activated sludge and trickling filters are two of the most common means of secondary treatment. It is accomplished by bringing together waste, bacteria, and oxygen in trickling filters or in the activated sludge process. This treatment removes floating and settleable solids and about 90 percent of the oxygen-demanding substances and suspended solids. Disinfection is the final stage of secondary treatment.

c. Tertiary wastewater treatment--selected biological, physical, and chemical separation processes to remove organic and inorganic substances that resist conventional treatment practices; the additional treatment of effluent beyond that of primary and secondary treatment methods to obtain a very high quality of effluent.

*Water quality*

(1) A term used to describe the chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose.

(2) A neutral term that relates to the composition of water as affected by natural processes and human activities. It depends not only on water's chemical condition, but also its biological, physical and radiological condition. The quality of water is

also related to specific use, and is usually measured in terms of constituent concentrations. The level of water quality is based upon the evaluation of measured quantities and parameters, which then are compared to water quality standards, objectives or criteria.

*Water treatment*

(1) Processes undertaken to purifier water acceptable to some specific use, e.g., drinking. Most water treatment processes include some form, or combination of forms, of sedimentation, filtration, and chlorination.
(2) Water Treatment, Combined Technique — A relatively new water disinfection technique greatly reducing the need for chlorination while effectively destroying up to 99.9 percent of coliphage (intestinal bacteria) in raw water. The method combines two purification techniques that have been previously used separately for water purification — potassium permanganate and copper/silver ions — but in combination the processes kill bacteria up to 10 times faster than metal ions alone and up to five times faster than potassium permanganate alone.

*Watershed*

(1) The land area that drains water to a particular stream, river, or lake. It is a land feature that can be identified by tracing a line along the highest elevations between two areas on a map, often a ridge, by topographic divides that drains a given stream or river.
(2) The natural or disturbed unit of land on which all of the water that falls (or emanates from springs or melts from snowpacks), collects by gravity, and fails to evaporate, runs off via a common outlet.
(3) All lands enclosed by a continuous hydrologic drainage divide and lying upslope from a specified point on a stream; a region or area bounded peripherally by a water parting and draining ultimately to a particular water course or body of water. Also referred to as Water Basin or Drainage Basin.

*Well*

(1) An artificial excavation put down by any method for the purposes of withdrawing water from the underground aquifers. A bored, drilled, or driven shaft, or a dug hole whose depth is greater than the largest surface dimension and whose purpose is to reach underground water supplies or oil, or to store or bury fluids below ground.
(2) An excavation (pit, hole, tunnel), generally cylindrical in form and often walled in, drilled, dug, driven, bored, or jetted into the ground to such a depth as to penetrate water-yielding geologic material and allow the water to flow or to be pumped to the surface.

Dug well – a shallow large diameter well constructed by excavating with hand tools or power machinery instead of by drilling or driving, such as a well for individual domestic water supplies.
Drilled well - a well constructed by cable tool or rotary drilling methods in search for water, oil or gas.

*Wetland (includes marsh, peat, bog, fen*)

(1) An area that is periodically inundated or saturated by surface or groundwater on an annual or seasonal basis, that displays hydric soils, and that typically supports or is capable of supporting hydrophytic vegetation.
(2) Wetlands are those areas where water saturation is the dominant factor determining the nature of soil development and the types of plant and animal communities living in the surrounding environment.
(3) The single feature that all wetlands have in common is a soil or substrate that is saturated with water during at least a part of the growing season. These saturated conditions control the types of plants and animals that live in these areas. Other common names for wetlands are Sloughs, Ponds, Swamps, Bogs, and Marshes. Basically, all definitions of wetlands require that one or more attributes be met:

a. Wetland Hydrology — At some point of time in the growing season the substrate is periodically or permanently saturated with or covered by water;
b. Hydrophytic Vegetation — At least periodically, the land supports predominantly water-loving plants such as cattails, rushes, or sedges;
c. Hydric Soils — The area contains undrained, wet soil which is anaerobic, or lacks oxygen in the upper levels.

*Zooplankton*

Small protozoans or metazoans (e.g, invertebrates and other animals) that feed on other planktonic organisms that inhabit the water column of bodies of water.

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http://www.oceansatlas.com/unatlas/uses/uneptextsph/infoph/gsglossary.html

Unistates, http://unistates.com/rmt/explained/glossary/rmtglossarylmn.html

University of Florida, http://aquat1.ifas.ufl.edu/glossary.html

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http://www.nps.gov/grsa/resources/curriculum/glossary.htm

U.S. Environment Protection Agency, http://www.epa.gov/watertrain/cwa/glossary.htm

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http://ga.water.usgs.gov/edu/dictionary.html

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## Annex 1: Guidelines and Standards for Drinking Water Quality

**Introduction**

> *Drinking-water quality is an issue of concern for human health in developing and developed countries world-wide. The risks arise from infectious agents, toxic chemicals and radiological hazards. Experience highlights the value of preventive management approaches spanning from water resource to consumer.*
> Source: WHO, http://www.who.int/

The international governing community has agreed, through the Millennium Development Goals, to reduce by half the proportion of people without sustainable access to safe drinking water and improved access to sanitation by 2015. To provide safe water, there is a need to ensure that the quality of drinking water is assessed and monitored.

Typically, drinking water quality is assessed by comparisons of water samples to drinking water quality guidelines or standards. These guidelines and standards provide for the protection of human health, by ensuring that clean and safe water is available for human consumption. This document provides a global review of drinking water quality and standards used around the world.

There is a distinction between the two terms, *guidelines* and *standards*. The World Health Organization (WHO), Drinking Water Quality Guidelines provide international norms on water quality and human health that are used as the basis for regulation and standard setting, in developing and developed countries world-wide. These guidelines are adopted by many countries as national guidelines to follow, even if they are not necessarily enforceable by law. In contrast, drinking water quality standards are primarily set by nation states and can be enforceable by law. For example, the Environmental Protection Agency (EPA) of the United States of America has two sets of standards: the Primary Standards, that directly link human safety to drinking water and are enforceable by law, and the Secondary Standards, that relate to cosmetic and aesthetic effects and are not legally required.

Another example of binding standards is the Water Framework Directive set out by the European Union. Under Council Directive 98/83/EU, the Union provides Drinking Water parameters which include an obligation for EU member countries to inform the consumer on drinking water quality and measures that they can take to comply with the requirements of the Water Directive. EU members have agreed to comply with these parameters.

Many countries set drinking water quality guidelines based on the WHO guidelines but may modify these based on what is achievable in-country. For example, the financial requirements and infrastructure needed to monitor and assess drinking water quality can be limiting in some developing countries. For these and other reasons, the guidelines may also vary between rural areas and urban centers within a country.

UNEP's GEMS/Water Programme conducts research on water quality guidelines for the Protection of Aquatic Ecosystem Health with much the same approach, in an attempt to provide data on this issue from a global perspective. Table 5 details the guidelines or standards to which a country adheres; Table 6 is a country list that indicates which countries have guidelines or standards, and if they are national or following an international set of guidelines or standards (i.e. WHO guidelines); and Table 7 provides a list of sources, primarily websites, from where the guidelines or standards were retrieved.

Table 5. Summary of water quality guidelines and standards by international organization or country

| **Geographic Region Þ** | **WHO (Guidelines)** | **European Union (Standards)** | **Canada (Guidelines)** | **Australia (Guidelines)** | **New Zealand (Guidelines)** | **Japan (Standards)** | **United States (Standards)** |
|---|---|---|---|---|---|---|---|
| **Parameter ⇓** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** |
| **Algae, blue-green** | | | | | >1 toxic/10 mL | | |
| **Alkalinity** | | | | | | | |
| **Aluminum** | 0.2 | 0.2 | 0.2 | 0.2 | | 0.2 | 0.2 |
| **Ammonia – un-ionized** | * | 0.5 | 0.5 | 0.5 | | | |
| **Ammonia – total** | | | | | | | |
| **Antimony** | 0.005 | 0.005 | 0.006 | 0.003 | 0.003 | | 0.006 |
| **Arsenic** | 0.01 | 0.01 | 0.01 | 0.007 | 0.01 | 0.01 | 0 |
| **Barium** | 0.3 | # | | 0.7 | 0.7 | | 2 |
| **Beryllium** | * | # | | | 0.004 | | 0.004 |
| **Bismuth** | | | | | | | |
| **Boron** | 0.3 | 0.001 | 0.001 | 4 | 1.4 | 1 | |
| **Bromate** | * | 0.01 | 0.01 | 0.02 | 0.025 | 0.01 | 0 |
| **Cadmium** | 0.003 | 0.005 | 0.005 | 0.002 | 0.003 | 0.01 | 0.005 |
| **Calcium** | * | | | | | 300 | |
| **Chloride** | 250 | 250 | 250 | 250 | | 200 | 250 |
| **Chloroph A** | | | | | | | |
| **Chromium** | 0.05 | 0.05 | 0.05 | | 0.05 | 0.05 | 0.1 |
| **Cobalt** | | | | | | | |
| **Coliform – fecal** | # | | | | | | |
| **Coliform – total** | # | 0/100 mL | 0/100mL | | | 0 | 0 |

| Geographic Region Þ | WHO (Guidelines) | European Union (Standards) | Canada (Guidelines) | Australia (Guidelines) | New Zealand (Guidelines) | Japan (Standards) | United States (Standards) |
|---|---|---|---|---|---|---|---|
| **Parameter ⇓** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** | **mg $L^{-1}$** |
| **Colour** | # | # | & | | | >5 degrees | 15 colour units |
| **Conductivity** | ^ | ^ | ^ | | | | |
| **Copper** | 2 | 2 | 2 | 1 | 2 | 1 | 1.3 |
| **Cyanide** | 0.07 | 0.05 | 0.05 | 0.08 | 0.08 | 0.01 | 0.2 |
| **Enterococci** | | 0/250 mL | 0/250mL | | | | |
| **Escherichia coli** | | 0/250 mL | 0/250mL | | >1/100mL | | |
| **Fluoride** | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 0.8 | 2 |
| **Fluoride – inorganic** | | | | | | | |
| **DOC** | | | | | | | |
| **Hardness** | * | # | | & | | 300 | |
| **Iron** | # | 0.2 | 0.2 | 0.3 | 0.01 | 0.3 | 0.3 |
| **Lead** | 0.01 | 0.01 | 0.01 | | 0.01 | 0.01 | 0 |
| **Lithium** | | | | | 0.9 | | |
| **Magnesium** | | | | | | 300 | |
| **Manganese** | 0.5 | 0.05 | 0.05 | 0.5 | 0.5 | 0.05 | 0.05 |
| **Mercury** | 0.001 | 0.001 | 0.001 | 0.001 | 0.002 | 0.0005 | |
| **Mercury – inorganic** | | | | | | | 0.002 |
| **Methylmercury** | | | | | | | |
| **Molybdenum** | 0.07 | # | | 0.05 | 0.07 | | |
| **Nickel** | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | | |
| **Nitrate** | | 50 | 50 | | 50 | | 10 |
| **Nitrate + Nitrite** | 50 | | | | | 10 | |
| **Nitrite** | | 0.5 | 0.5 | | 3 | | 1 |
| **Odour** | | & | & | | | & | |
| **Oil & grease** | | | | | | | |
| **Ortho-P** | | | | | | | |
| **Oxygen - dissolved** | | | | | | | |
| **Particulate matter <2.5 µm (PM<2.5)** | | | | | | | |
| **pH** | * | # | | 6.5-8.5 | | 5.8-8.6 | 6.5-8.5 |
| **Phosphorus - total** | | | | | | | |

| Geographic Region Þ<br>Parameter ⇓ | WHO (Guidelines)<br>mg $L^{-1}$ | European Union (Standards)<br>mg $L^{-1}$ | Canada (Guidelines)<br>mg $L^{-1}$ | Australia (Guidelines)<br>mg $L^{-1}$ | New Zealand (Guidelines)<br>mg $L^{-1}$ | Japan (Standards)<br>mg $L^{-1}$ | United States (Standards)<br>mg $L^{-1}$ |
|---|---|---|---|---|---|---|---|
| **Potassium** | | | | | | | |
| **Rubidium** | | | | | | | |
| **Salinity** | | | | | | | |
| **Selenium** | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 |
| **Silver** | # | # | | 0.1 | 0.02 | | 0.1 |
| **Sodium** | 200 | 200 | 200 | 180 | | 200 | |
| **Solids - total dissolved (TDS)** | * | # | | & | | | 500 |
| **Solids - total suspended (TSS)** | * | # | | | | | |
| **Strontium - 90** | | | | | | | |
| **Sulfate** | 500 | 250 | 250 | 500 | | | 250 |
| **Temperature** | | | | | | | |
| **Thallium** | | | | | | | |
| **Tin** | * | # | | | 1 | | 0.0005 |
| **TOC** | | | | | | | |
| **Tritium** | | 100Bq/L | | | | | |
| **Turbidity** | * | # | & | | | >2 degrees | n/a |
| **Uranium** | * | # | 0.02 | 0.02 | 0.002 | | |
| **Vanadium** | 1.4 | # | | | | | |
| **Zinc** | 3 | # | | 3 | | 1 | 5 |
| | | | | | | | |

*: no guideline
#: not mentioned
^: 250 µS $cm^{-1}$
&: acceptable to consumers no abnormal changes

Table 6. Summary of drinking water guidelines or standards by country

| | COUNTRY | GUIDELINES |
|---|---|---|
| 1. | Afghanistan | No guidelines as yet |
| 2. | Albania | |
| 3. | Algeria | WHO |
| 4. | American Samoa | |
| 5. | Andorra | |
| 6. | Angola | WHO |
| 7. | Anguilla | |
| 8. | Antarctica | |
| 9. | Antigua and Barbuda | |
| 10. | Argentina | |
| 11. | Armenia | |
| 12. | Aruba | |
| 13. | Ashmore & Cartier Islands (Australia) | |
| 14. | Australia | Country specific |
| 15. | Austria | European Union Water Framework Directive |
| 16. | Azerbaijan | |
| 17. | Bahamas, The | |
| 18. | Bahrain | |
| 19. | Baker & Howland Islands | |
| 20. | Bangladesh | |
| 21. | Barbados | |
| 22. | Belarus | |
| 23. | Belgium | European Union Water Framework Directive |
| 24. | Belize | |
| 25. | Benin | More strict than WHO |
| 26. | Bermuda | |
| 27. | Bhutan | |
| 28. | Bolivia | |
| 29. | Bosnia and Herzegovina | |
| 30. | Botswana | WHO |
| 31. | Bouvet Island (Norwegian) | |
| 32. | Brazil | |
| 33. | British Indian Ocean Territory | |
| 34. | British Virgin Islands (Britain) | |
| 35. | Brunei Darussalam | |
| 36. | Bulgaria | |
| 37. | Burkina Faso | WHO |
| 38. | Burundi | No guidelines as yet |
| 39. | Cambodia | |
| 40. | Cameroon | Have (haven't found them yet) |
| 41. | Canada | Country specific |
| 42. | Canary Islands | |
| 43. | Cape Verde | |
| 44. | Cayman Islands (British) | |
| 45. | Central African Republic | |
| 46. | Chad | More strict than WHO |
| 47. | Chile | |
| 48. | China | |
| 49. | Christmas Island | |
| 50. | Cocos Islands (Australian) | |

| | COUNTRY | GUIDELINES |
|---|---|---|
| 51. | Colombia | |
| 52. | Comoros | |
| 53. | Congo | No guideline as yet |
| 54. | Cook Islands (New Zealand) | |
| 55. | Coral Sea Islands (Australian) | |
| 56. | Costa Rica | |
| 57. | Côte d´Ivoire | |
| 58. | Croatia | |
| 59. | Cuba | |
| 60. | Cyprus | European Union Water Framework Directive |
| 61. | Czech Republic | European Union Water Directive |
| 62. | Democratic Republic of the Congo | |
| 63. | Denmark | European Union Water Directive |
| 64. | Djibouti | |
| 65. | Dominica | |
| 66. | Dominican Republic | |
| 67. | Ecuador | |
| 68. | Egypt | |
| 69. | El Salvador | |
| 70. | Equatorial Guinea | |
| 71. | Eritrea | WHO |
| 72. | Estonia | European Union Water Framework Directive |
| 73. | Ethiopia | WHO |
| 74. | Faeroe Islands (British) | |
| 75. | Falkland Islands (British) | |
| 76. | European Community | |
| 77. | Fiji | |
| 78. | Finland | European Union Water Framework Directive |
| 79. | France | European Union Water Framework Directive |
| 80. | French Guiana (French) | |
| 81. | French Polynesia (French) | |
| 82. | Gabon | WHO |
| 83. | Gambia, The | WHO |
| 84. | Georgia | |
| 85. | Germany | European Union Water Framework Directive |
| 86. | Ghana | WHO |
| 87. | Gibraltar (British) | |
| 88. | Greece | European Union Water Directive |
| 89. | Greenland (Denmark) | |
| 90. | Grenada | |
| 91. | Guadeloupe (French) | |
| 92. | Guam (United States) | |
| 93. | Guatemala | |
| 94. | Guernsey (British) | |
| 95. | Guinea | More strict than WHO |
| 96. | Guinea-Bissau | WHO |
| 97. | Guyana | |
| 98. | Haiti | |
| 99. | Heard & MacDonald Islands (Australia) | |
| 100. | Holy See | |
| 101. | Honduras | |
| 102. | Hong Kong | |

| | COUNTRY | GUIDELINES |
|---|---|---|
| 103. | Hungary | European Union Water Framework Directive |
| 104. | Iceland | |
| 105. | India | |
| 106. | Indonesia | |
| 107. | Iran (Islamic Republic of) | |
| 108. | Iraq | |
| 109. | Ireland | European Union Water Framework Directive |
| 110. | Isle of Man (British) | |
| 111. | Israel | |
| 112. | Italy | European Union Water Framework Directive |
| 113. | Jamaica | |
| 114. | Jan Mayen (Norwegian) | |
| 115. | Japan | Country specific |
| 116. | Jarvis Island (United States) | |
| 117. | Jersey (British) | |
| 118. | Johnston Atoll (United States) | |
| 119. | Jordan | |
| 120. | Kazakhstan | No guidelines as yet |
| 121. | Kenya | WHO |
| 122. | Kingman Reef (United States) | |
| 123. | Kiribati | |
| 124. | Korea (Democratic People's Republic of) | |
| 125. | Korea (Republic of) | |
| 126. | Kuwait | |
| 127. | Kyrgyzstan | No guidelines as yet |
| 128. | Lao People's Democratic Republic | |
| 129. | Latvia | European Union Water Framework Directive |
| 130. | Lebanon | |
| 131. | Lesotho | Less strict than the WHO |
| 132. | Liberia | WHO |
| 133. | Libyan Arab Jamahiriya | |
| 134. | Liechtenstein | |
| 135. | Lithuania | European Union Water Framework Directive |
| 136. | Luxembourg | European Union Water Framework Directive |
| 137. | Macao (China) | |
| 138. | Macedonia, The Former Yugoslav Republic of | |
| 139. | Madagascar | WHO |
| 140. | Malawi | Less strict than the WHO |
| 141. | Malaysia | |
| 142. | Maldives | |
| 143. | Mali | No guidelines as yet |
| 144. | Malta | European Union Water Directive |
| 145. | Marshall Islands (United States) | |
| 146. | Martinique (French) | |
| 147. | Mauritania | WHO |
| 148. | Mauritius | WHO |
| 149. | Mayotte (French) | |
| 150. | Mexico | |
| 151. | Micronesia, Federated States of | |
| 152. | Midway Islands (United States) | |
| 153. | Moldova, Republic of | |
| 154. | Monaco | |

| | COUNTRY | GUIDELINES |
|---|---|---|
| 155. | Mongolia | |
| 156. | Montserrat (British) | |
| 157. | Morocco | |
| 158. | Mozambique | |
| 159. | Myanmar | |
| 160. | Namibia | WHO |
| 161. | Nauru | |
| 162. | Navassa Island (United States) | |
| 163. | Nepal | |
| 164. | Netherlands Antilles (Dutch) | |
| 165. | Netherlands | European Union Water Framework Directive |
| 166. | New Caledonia (French) | |
| 167. | New Zealand | Country specific |
| 168. | Nicaragua | |
| 169. | Niger | WHO |
| 170. | Nigeria | No guidelines as yet |
| 171. | Niue (New Zealand) | |
| 172. | Norfolk Island (Australian) | |
| 173. | Northern Mariana Islands (United States) | |
| 174. | Norway | |
| 175. | Oman | |
| 176. | Pakistan | |
| 177. | Palau | |
| 178. | Palestine | |
| 179. | Palmyra Atoll (United States) | |
| 180. | Panama | |
| 181. | Papua New Guinea | |
| 182. | Paracel Islands | |
| 183. | Paraguay | |
| 184. | Peru | |
| 185. | Peter Islands (Norwegian) | |
| 186. | Philippines | |
| 187. | Pitcairn Islands (British) | |
| 188. | Poland | European Union Water Framework Directive |
| 189. | Portugal | European Union Water Framework Directive |
| 190. | Puerto Rico (United States) | |
| 191. | Qatar | |
| 192. | Reunion (French) | |
| 193. | Romania | |
| 194. | Russian Federation | |
| 195. | Rwanda | WHO |
| 196. | Saint Kitts and Nevis | |
| 197. | Saint Lucia | |
| 198. | Saint Vincent and the Grenadines | |
| 199. | Samoa | |
| 200. | San Marino | |
| 201. | Sao Tome and Principe | |
| 202. | Saudi Arabia | |
| 203. | Senegal | WHO |
| 204. | Serbia and Montenegro | |
| 205. | Seychelles | WHO |
| 206. | Sierra Leone | WHO |

| | COUNTRY | GUIDELINES |
|---|---|---|
| 207. | Singapore | |
| 208. | Slovakia | European Union Water Framework Directive |
| 209. | Slovenia | European Union Water Framework Directive |
| 210. | Solomon Islands | |
| 211. | Somalia | |
| 212. | South Africa | Country specific |
| 213. | S. Georgian & S. Sandwich Islands (British) | |
| 214. | Spain | European Union Water Framework Directive |
| 215. | Spratly Islands | |
| 216. | Sri Lanka | |
| 217. | St. Helena & Dependencies (British) | |
| 218. | St. Pierre & Miquelon (French) | |
| 219. | Sudan | |
| 220. | Suriname | |
| 221. | Svalbard (Norwegian) | |
| 222. | Swaziland | WHO |
| 223. | Sweden | European Union Water Framework Directive |
| 224. | Switzerland | |
| 225. | Syrian Arab Republic | |
| 226. | Taiwan | |
| 227. | Tajikistan | |
| 228. | Tanzania, The United Republic of | Less strict than the WHO |
| 229. | Thailand | |
| 230. | Timor Leste | |
| 231. | Togo | |
| 232. | Tokelau (New Zealand) | |
| 233. | Tonga | |
| 234. | Trinidad and Tobago | |
| 235. | Tunisia | |
| 236. | Turkey | |
| 237. | Turkmenistan | |
| 238. | Turks & Caicos Islands (British) | |
| 239. | Tuvalu | |
| 240. | Uganda | WHO |
| 241. | Ukraine | |
| 242. | United Arab Emirate | |
| 243. | United Kingdom of Great Britain and Northern Ireland | European Union Water Framework Directive |
| 244. | United States of America | Country specific |
| 245. | Uruguay | |
| 246. | Uzbekistan | No guidelines as yet |
| 247. | Vanuatu | |
| 248. | Venezuela | |
| 249. | Viet Nam | |
| 250. | Virgin Islands (United States) | |
| 251. | Wake Island (United States) | |
| 252. | Wallis & Futuna (French) | |
| 253. | Yemen | |
| 254. | Zambia | WHO |
| 255. | Zimbabwe | WHO |

Table 7. Sources for drinking water quality guidelines and/or standards

| Country | Source |
|---|---|
| Algeria (2000) | http://www.afro.who.int/wsh/countryprofiles/algeria.pdf |
| Angola | http://www.afro.who.int/wsh/countryprofiles/angola.pdf |
| Anguilla | http://www.paho.org/english/sha/prflang.htm |
| Australia | http://www.nhmrc.gov.au/publications/_files/awg3.pdf |
| Benin | http://www.afro.who.int/wsh/countryprofiles/benin.pdf |
| Botswana | http://www.afro.who.int/wsh/countryprofiles/botswana.pdf |
| Burkina Faso | http://www.afro.who.int/wsh/countryprofiles/burkinafaso.pdf |
| Burundi | http://www.afro.who.int/wsh/countryprofiles/burundi.pdf |
| Cameroon | http://www.afro.who.int/wsh/countryprofiles/cameroon.pdf |
| Canada | http://www.agr.gc.ca/pfra/water/domestwq_e.htm and www.ec.gc.ca |
| Chad | http://www.afro.who.int/wsh/countryprofiles/chad.pdf |
| Congo | http://www.afro.who.int/wsh/countryprofiles/congo.pdf |
| Eritrea | http://www.afro.who.int/wsh/countryprofiles/eritrea.pdf |
| Ethiopia | http://www.afro.who.int/wsh/countryprofiles/ethiopia.pdf |
| European Union (1998) | http://www.lenntech.com/EU's-drinking-water-standards.htm |
| Gabon | http://www.afro.who.int/wsh/countryprofiles/gabon.pdf |
| Gambia, The | http://www.afro.who.int/wsh/countryprofiles/gambia.pdf |
| Ghana | http://www.afro.who.int/wsh/countryprofiles/ghana.pdf |
| Guinea | http://www.afro.who.int/wsh/countryprofiles/guinea.pdf |
| Guinea-Bissau | http://www.afro.who.int/wsh/countryprofiles/guineabissau.pdf |
| Japan | http://www.jwwa.or.jp/water-e07.html |
| Kazakhstan | http://www.euro.who.int/document/wsn/Mtgrpt021128.pdf |
| Kenya | http://www.afro.who.int/wsh/countryprofiles/kenya.pdf |
| Kyrgyzstan | http://www.euro.who.int/document/wsn/Mtgrpt021128.pdf |
| Lesotho | http://www.afro.who.int/wsh/countryprofiles/lesotho.pdf |
| Liberia | http://www.afro.who.int/wsh/countryprofiles/liberia.pdf |
| Madagascar | http://www.afro.who.int/wsh/countryprofiles/madagascar.pdf |
| Malawi | http://www.afro.who.int/wsh/countryprofiles/malawi.pdf |
| Mali | http://www.afro.who.int/wsh/countryprofiles/mali.pdf |
| Mauritania | http://www.afro.who.int/wsh/countryprofiles/mauritania.pdf |
| Mauritius | http://www.afro.who.int/wsh/countryprofiles/mauritius.pdf |
| Namibia | http://www.afro.who.int/wsh/countryprofiles/namibia.pdf |
| New Zealand (2000) currently under review | http://www.moh.govt.nz/moh.nsf |
| Niger | http://www.afro.who.int/wsh/countryprofiles/niger.pdf |
| Nigeria | http://www.afro.who.int/wsh/countryprofiles/nigeria.pdf |
| Rwanda | http://www.afro.who.int/wsh/countryprofiles/rwanda.pdf |
| Senegal | http://www.afro.who.int/wsh/countryprofiles/senegal.pdf |
| Seychelles | http://www.afro.who.int/wsh/countryprofiles/seychelles.pdf |
| Sierra Leone | http://www.afro.who.int/wsh/countryprofiles/sierraleone.pdf |
| South Africa | http://www.stansa.co.za (available for purchase only) |

| Country | Source |
| --- | --- |
| Swaziland | http://www.afro.who.int/wsh/countryprofiles/swaziland.pdf |
| Tanzania | http://www.afro.who.int/wsh/countryprofiles/tanzania.pdf |
| Uganda | http://www.afro.who.int/wsh/countryprofiles/uganda.pdf |
| United States | http://www.epa.gov/safewater/mcl.html#mcls |
| Uzbekistan | http://www.euro.who.int/document/wsn/Mtgrpt021128.pdf |
| WHO | http://www.who.int/water_sanitation_health/dwq/en/ |
| Zambia | http://www.afro.who.int/wsh/countryprofiles/zambia.pdf |
| Zimbabwe | http://www.afro.who.int/wsh/countryprofiles/zimbabwe.pdf |