WATER QUALITY

Overview

The definition of water quality is not objective, but is socially defined depending on the desired use of water. Different uses require different standards of water quality. Water used for hydropower generation, industrial purposes, and transportation does not require high standards of purity. Such uses as recreation, fishing, drinking, and habitat for aquatic organisms rely on higher levels of water quality (UN/ECE 1995:5, 6). For that reason, water quality should be taken to mean the "physical, chemical, and biological characteristics of water necessary to sustain desired water uses" (UN/ECE 1995:5).

Monitoring the quality of water is important because clean water is necessary for human health and the integrity of aquatic ecosystems. Ecosystems filter and cleanse water. For instance, wetlands provide a very important service because they filter water by intercepting surface runoff, trapping sediments, and removing nitrogen and minerals from the water. This water filtering service has been estimated to be worth US$3 million a year for just a 5.5-kilometer stretch of the Alchovy River in the State of Georgia in the United States (Lerner and Poole 1999:41). This ability to filter and purify water, however, is being impaired by pollution and habitat degradation in many rivers, lakes, and estuaries around the world. As much as 3.3 billion people still lack access to adequate sanitation and more than a billion people lack access to safe drinking water, leading to millions of deaths and illnesses each year, mostly in the developing world (Cosgrove and Rijsberman 2000:9 and WHO 1996).

Most water quality monitoring was originally conducted at known sources of pollution, but this approach failed to detect the many diffuse nonpoint sources of water pollution. To overcome this deficiency, water quality monitoring has evolved along two different lines. One is a river basin approach. In the United States, this approach is used by the Environmental Protection Agency (EPA) in its Index of Watershed Indicators (IWI), and by the U.S. Geological Survey (USGS) with the National Water-Quality Assessment (NAWQA) Program. The IWI is briefly described in Box 2. The NAWQA program provides data on nutrients, pesticides, and volatile organic compounds for surface and groundwater in 60 important river basins and aquifers across the country. These programs generally examine only the physical and chemical qualities and quantities of water. One potential problem with river basin-level approaches is that such basins often cross state and national boundaries, necessitating the

Box 2

Index of Watershed Indicators from the U.S. Environmental Protection Agency

To better communicate water pollution problems and address water quality issues in the United States, the Environmental Protection Agency (EPA) has developed an Index of Watershed Indicators (IWI) for 2,262 watersheds. It integrates 15 indicators of watershed condition and vulnerability. The condition indicators are based on a range of variables, including the number of fish consumption alerts by watershed, data on contaminated sediments from sampling stations, recent and historical loss of wetlands, and water quality reports measured against state and tribal water quality standards designated for that particular water body.

In addition, the EPA uses another eight indicators to describe watershed vulnerability. These vulnerability indicators represent pressures on freshwater systems that are linked to water degradation and habitat quality in watersheds. They include the number of aquatic or wetland species at risk, the discharged loads of pollutants, and the potential impact of urban and agricultural runoff.

The EPA uses different weighting schemes to aggregate indicators of watershed condition and vulnerability into the IWI, assigning scores for each watershed assessed. Based on these scores, watersheds are classified into seven categories:

1. Watersheds with better water quality and lower vulnerability to stressors, such as pollutant loadings;
2. Watersheds with better water quality and higher vulnerability to stressors;
3. Watersheds with less serious water quality problems and lower vulnerability to stressors;
4. Watersheds with less serious water quality problems and higher vulnerability to stressors;
5. Watersheds with more serious water quality problems and lower vulnerability to stressors;
6. Watersheds with more serious water quality problems and higher vulnerability to stressors;
7. Watersheds with insufficient data to be assessed for water quality and vulnerability.

There has to be a minimum of 10 of the indicators in order for a watershed to get an "IWI score." Otherwise the watershed is characterized as having "insufficient data."

The following table presents the results for 1999:

IWI	**Number of Watersheds**
Better Water Quality–Low Vulnerability	310
Better Water Quality–High Vulnerability	29
Less Serious Water Quality Problems–Low Vulnerability	736
Less Serious Water Quality Problems–High Vulnerability	58
More Serious Water Quality Problems–Low Vulnerability	496
More Serious Water Quality Problems–High Vulnerability	38
Insufficient Data	595

Overall 32 percent of those watersheds with sufficient data to be scored are classified as having serious water quality problems and 48 percent are classified as having less serious water quality problems. It is also important to note that even in the United States, where data collection on water quality is more systematic than in many other countries, regulators lack the information to assess 26 percent of the watersheds selected for this index.

Source: EPA 1999.

need for a high level of governmental or intergovernmental coordination of monitoring activities.

Another approach to water quality monitoring is an integration of chemical and biological parameters to measure condition. Whereas biological measures of water quality do not eliminate the need for chemical water monitoring, they are often less expensive than chemical analyses and can provide a useful index of potential chemical pollution problems (UN/ECE 1995:9, 10). Biological monitoring programs are used to measure water quality standards in the United States, the United Kingdom, and Australia, and have been applied in a number of other countries around the world.

This section will examine different measures of surface and groundwater quality in use around the world, and will briefly examine trends in the water quality of rivers and streams. It will focus on Europe and the United States because trend data for other regions of the world are not as readily available (Shiklomanov 1997:27).

The quality of surface waters in industrialized countries has generally been improving with respect to some pollutants over the last 20 years, but new chemicals are increasingly becoming a problem. For example, in most developed countries waste treatment plants have considerably reduced fecal contamination of surface waters. However, in developing countries sewage treatment is still not the norm, with 90 percent being discharged directly into rivers, lakes, and coastal areas without any treatment (WRI 1996:21). Consequently, water-related diseases, such as cholera, amoebic dysentery, schistosomiasis, malaria, and trypanosomiasis among others, claim 5 million lives annually worldwide and cause illness in perhaps half of the population of the developing world each year (WHO 1996). New pollution problems from agricultural and industrial sources have emerged in both industrialized and developing countries, and have become one of the biggest challenges facing water resources in many parts of the world (Shiklomanov 1997:36).

Fortunately methods for monitoring change have improved as well. Many states and countries have moved beyond the conventional monitoring methods toward biological indicators of water quality. These are discussed in greater detail later. Groundwater resources are also important. Because groundwater is hidden from view, many pollution and contamination problems that affect supplies have been more difficult to detect and have only recently been discovered.

Condition Indicators of the Quality of Surface Waters

Information about water quality at the global level is poor and difficult to obtain for a number of reasons. Water quality problems are often local and natural water quality is highly variable depending on the location, season, or even time of day. Global criteria for water quality are, therefore, difficult to construct (Shiklomanov 1997:27).

However, there are many trends in the contamination of water supplies worldwide, and these have changed greatly over time. The main contamination problems 100 years ago were fecal and organic pollution from untreated human wastewater. The fecal contamination of water has been largely eliminated in most industrialized countries; however, organic matter pollution is still a problem in much of the world, especially in rapidly expanding cities in developing countries (Shiklomanov 1997:28). New pollution problems, particularly from agricultural runoff and industrial effluents, are increasing in both industrialized and developing countries. In rapidly industrializing countries, such as China, India, Mexico, and Brazil, untreated sewage and industrial wastes create substantial pressures on water quality that are much greater than the problems of the past (Shiklomanov 1997:27; UNEP/GEMS 1995:6).

A number of chemical, physical, and microbial factors negatively affect water quality (Taylor and Smith 1997; Shiklomanov 1997; UNEP/GEMS 1995). These include the following:

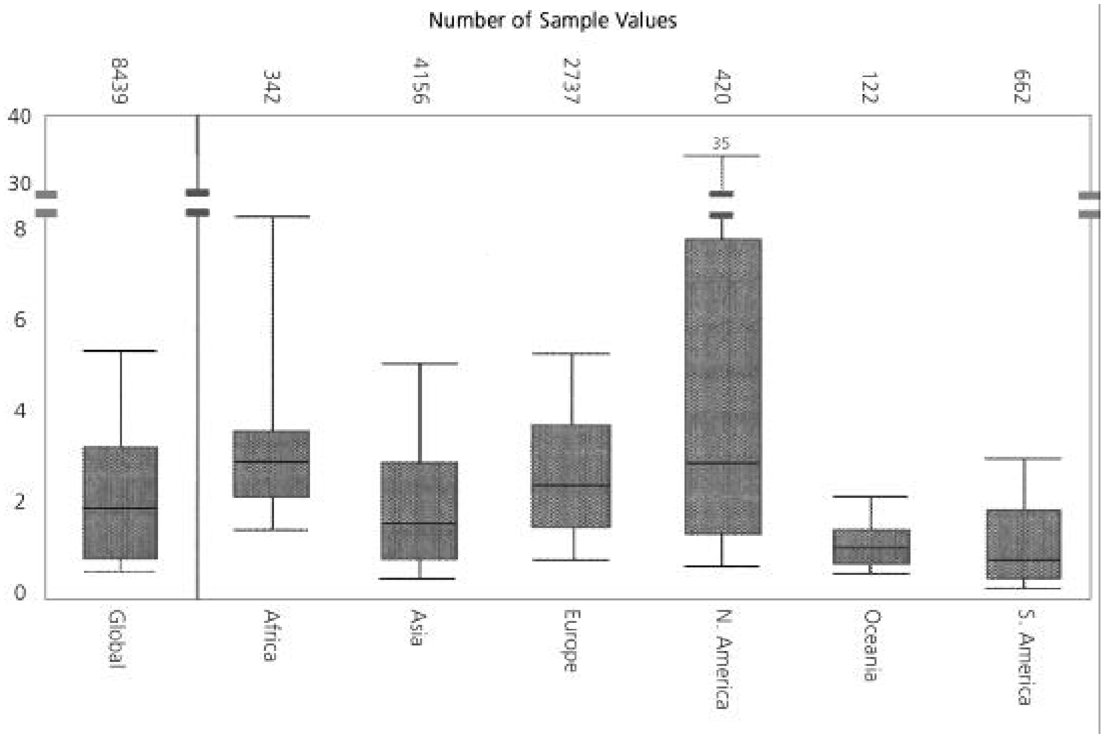
- Organic pollutants. Organic matter is a problem because it easily decomposes in water, consuming dissolved oxygen in the process. This often leads to the eutrophication and deoxygenation of waterways, with negative effects for aquatic life. The process also releases ammonium, which when converted to ammonia by natural chemical processes, is poisonous to fish. The primary sources of organic matter in lakes and rivers are wastewater from industrial plants and domestic sewage.
- Nutrients. Increased nutrient concentrations in freshwater, such as phosphorus and nitrates, can also cause eutrophication in lakes and rivers by decreasing the amount of oxygen available to aquatic life. This kills fish and other aquatic organisms. High levels of nitrates, when ingested in drinking water, restrict oxygen transport in the human bloodstream and can lead to illness.
- Heavy metals. These can be a severe problem because they accumulate in the tissues of fish and shellfish and are highly toxic. They also persist for long periods of time in freshwater ecosystems. Heavy metal pollution tends to be localized around industrial and mining centers.
- Microbial contamination. The contamination of water by bacteria, protists, and amoebae also pose threats to human health though the spread of infectious diseases. Fecal contamination from untreated sewage, for instance, leads to outbreaks of diseases that claim millions of lives each year.
- Toxic organic compounds. These include oil, petroleum products, pesticides, plastics, and industrial chemicals. All these are toxic to aquatic fauna and humans.
- Salinization. Increasing levels of salinity from overirrigation and groundwater overabstraction renders freshwater supplies undrinkable and kills crops.
- Acidification. Decreasing pH levels in rivers and lakes because of sulfuric deposition created by industrial activity kills fish and also leaches trace metals from soils, which has negative effects on human health.
- Suspended particles. These can be from either inorganic or organic matter. They degrade habitats of aquatic organisms and reduce water quality for drinking and recreational uses.
- Temperature: The thermal characteristics of water are crucial for aquatic life. Temperature determines the rate of chemical and biological processes, such as algal growth and decomposition of organic matter. Fragmentation of rivers by dams and reservoirs, as well as industrial uses such as hydropower and cooling plants, impact water temperatures.

CHEMICAL METHODS OF WATER QUALITY MONITORING

The amount of organic matter in freshwater systems around the world can be gauged by the global distribution of biochemical oxygen demand (BOD) measurements, seen in Figure 3. BOD increases with the amount of organic matter in water and gives an indication for the potential of algal growth and eutrophication *(see following note on the definitions of BOD and chemical oxygen demand, or COD)*. The BOD concentration of clean freshwater is normally around 2 mg/l, whereas values exceeding 5 mg/l usually indicate pollution (EEA 1994:45). The values in

Figure 3

Statistical Distribution of BOD by Continent, 1976–90



Source: UNEP/GEMS 1995.

Note: In Figure 3, the median value is represented by a horizontal line inside each of the gray boxes. The gray boxes represent the 25th and 75th percentiles, respectively. The two horizontal lines outside each gray box represent the 10th and 90th percentiles, respectively. Biochemical oxygen demand (BOD) and chemical oxygen demand (COD) are two methods widely used to measure the amount of organic pollution in wastewater and streams. BOD-5 is the amount of oxygen consumed by micro-organisms in a water sample over 5 days at 20 degrees Celsius. COD is the amount of oxygen consumed under specific conditions in the oxidation of organic and oxidizable inorganic matter contained in water. It is an indirect measure of the amount of oxygen used by inorganic and organic matter in water. In undisturbed rivers, BOD is typically less than 2 mg O_2/L and COD is less than 20 mg O_2/L. COD is a laboratory test based on a chemical oxidant and, therefore, does not necessarily correlate with biochemical oxygen demand (EEA 1994 and EEA 1998).

Figure 3 are based on the U.N.'s Global Environment Monitoring System (GEMS/WATER) that measured water quality from 1976 to 1990 at approximately 175 stations in 82 major river basins around the world (UNEP/GEMS 1995).

Although the BOD figures vary greatly, it can be seen that the highest organic matter concentrations were found in North American waterways. Values for Europe and Africa were also above the global median of 2 mg/l. Africa had a very wide range of values, which might represent greater amounts of pollution in the Nile; however more information is needed to give these figures greater clarity. But even in regions where organic matter concentrations are relatively low, such as Oceania and South America, eutrophication can be an issue. For example, the problems associated with eutrophication became apparent in Australia when the world's largest algal bloom spread along a 1,000-kilometer stretch of the Darling River in 1991 (SEAC 1996:7.49–50). This bloom caused the closure of water supplies for numerous communities along the river, forcing them to use costly alternative supplies (SEAC 1996:7.49–50). In this case BOD figures alone cannot adequately measure water quality because increased phosphorous concentrations are also a factor in noxious algal blooms.

These global data should be interpreted with caution, because the numbers of sampling points per basin vary in time and space. Continents are not represented equally by sampling points and the sample values cover a 15-year period with significant changes in human activities and management.

A more recent assessment of the water quality in 1,000 European rivers shows that, in the mid-1990s, 35 percent of rivers had BOD levels below 2mg/l while 11 percent were heavily polluted with levels of BOD greater than 5 mg/l. Of these heavily polluted rivers, 25 percent were in southern and eastern Europe (EEA 1999:172). Because there is no single standardized system of water monitoring and assessment in Europe for surface waters, comparisons between data from different countries are somewhat difficult (EEA 1998).

Improved treatment of wastewater from households and industry has brought about reductions in organic matter concentrations across Europe in the last 20 years. The largest reductions have been found in Western Europe, where the percentage of heavily polluted rivers has fallen from 24 percent in the late 1970s to 6 percent in the 1990s (EEA 1999:172). In southern Europe, BOD concentrations have started to improve slightly over the last 15 years, but in eastern Europe they have decreased from a high of 40 percent in the early 1980s to less than 28 percent in the mid-1990s (EEA 1999:173). Nordic countries have seen no major change in BOD concentrations since the late 1970s, and the number of river stations above natural levels is still below 5 percent (EEA 1999:172–173).

The level of nutrients in freshwater systems is an increasing problem worldwide (Shiklomanov 1997:34–36). Natural waters have very small concentrations of nitrates and phosphorous. But these nutrients increase with runoff from agricultural lands (especially intensively cultivated lands with large inputs of synthetic fertilizers) and urban and industrial wastewater, creating eutrophication and human health hazards. GEMS/WATER has collected the only global data on phosphorous and nitrate concentrations. They include data for major watersheds covering the period from 1976 to 1990, which carry the same data limitations mentioned for the GEMS/WATER BOD measurements. Of these globally monitored watersheds, the highest nutrient concentrations can be seen for sampling stations in Europe. Nitrate concentrations are higher in watersheds that have been intensively used and modified by human activity, such as the Weser, Seine, Rhine, Elbe, and Senegal. In South America, nitrate concentrations in the monitored watersheds are relatively low and follow human land use. The highest nitrate concentrations are found in the Uruguay watershed, where some of the most intensive agriculture on the continent is found. Nitrate concentrations are also greater in the Magdalena watershed of Colombia than in the less densely populated watersheds of the Amazon basin (UNEP/GEMS 1995:33–35). The nitrate concentrations in South America correspond to lower fertilizer application rates, compared to Europe. These low fertilizer application rates match an analysis of nutrient balances carried out for the PAGE agroecosystem study (Wood et al. 2000).

In Europe, for which more detailed and recent data are available, the concentrations of nitrates and phosphorous in rivers show distinct regional trends. Nitrogen loadings are the highest in areas with intensive livestock and crop production, especially in the northern parts of western Europe. Nitrogen concentrations are the lowest in Finland, Norway, and Sweden. Overall nitrate concentrations in the monitored European rivers have not changed significantly since 1980, despite lower nitrogen fertilizer application rates since the 1990s (EEA 1998:194–197; EEA 1999:176–177). Similarly, rivers in Finland, Norway, and Sweden have the lowest phosphorous concentrations, whereas areas from southern England across central and western Europe show the highest levels (EEA 1999:174). Even though phosphorous concentrations have decreased significantly since 1985, mostly because of wastewater treatment and the reduced use of phosphorous in detergents, it remains a problem in most regions of Europe (EEA 1999:174). Despite some positive trends, the overall state of many European rivers remains poor (EEA 1998:194–196).

Table 4 shows water quality data for the United States for the 1980s. Although data on stream water quality are continuously monitored, these are the latest aggregated figures published for all monitoring stations.

For the 1980–89 period, nitrate concentrations remained relatively stable, with nearly the same number of stations demonstrating upward trends as downward trends. This probably reflects the fact that nitrogen fertilizer use in the United States leveled off after steady increases in the 1970s. Fertilizer application rates increased for the period 1974–1981, and nitrate concentrations increased as well during that period. Average

Table 4

Trends in U.S. Stream Water Quality, 1980–89

Water Quality Indicator	NASQAN Stations Analyzed	Upward Trend in Concentration	Downward Trend in Concentration	No Concentration Trend
		Number of Stations		
Dissolved Solids	340	28	46	266
Nitrate	344	22	27	295
Total Phosphorous	410	19	92	299
Suspended Sediments	324	5	37	282
Dissolved Oxygen	424	38	26	360
Fecal Coliform	313	10	40	263

Source: Data are from the USGS National Stream Quality Accounting Network (NASQAN), quoted in CEQ 1995.

nitrate concentrations were greater in agricultural and urban areas than in forested areas (Smith et al. 1994: 122).

Trends in phosphorous concentrations in the United States showed greater improvement, with five times more states showing downward trends than upward trends. Decreases were more likely to be found in the East, Midwest, and the Great Lakes regions, while the majority of increases occurred in the Southeast (Smith et al. 1994: 124).

The decreased concentrations of phosphorous in streams and rivers in the United States is attributable to reduced phosphorous in laundry detergents and improved controls in wastewater treatment plants. The increased number of sewage treatment plants has also reduced the amount of nitrogen in the form of ammonium, which is toxic to fish. However, the sewage treatment process converts ammonium to nitrates that are still released into waterways. Thus, the total amount of nitrogen flowing into waterways has not necessarily decreased with a greater number of sewage treatment facilities (Mueller and Helsel 1996).

Water quality programs in most OECD countries have been effective in reducing many kinds of chemical pollution in their waterways. The biggest reductions have been from point source pollutants. For example, in the United States from 1972 to 1992 the amount of sewage treated at wastewater treatment plants increased by 30 percent, yet BOD measurements of waters near these plants declined by 36 percent (CEQ 1995: 229). However, national programs have not been effective in reducing nonpoint source nutrients, sediments, and toxics that come from agriculture, urban and suburban stormwater runoff, mining, and oil and gas operations (NRC 1992:47;EEA 1999:178).

Similarly the existing data tell us little about the biological characteristics of inland waters because historically, water quality monitoring has focused on the measurement of chemical parameters. Although such information has provided important and predictive tools for evaluating water quality, the monitoring of biological indicators to assess the health of freshwater ecosystems is now also recognized as an important component of water quality monitoring programs. Beginning in the 1980s and increasingly in the last 10 years, a greater number of states in the United States and other countries are including biological monitoring as an important part of their overall water quality monitoring programs.

BIOLOGICAL METHODS OF WATER QUALITY MONITORING

Measurements of water quality based exclusively on chemical or physical properties are often used as surrogate measures of biological quality. But a reliance on these measures alone risks missing many important biological characteristics, such as habitat alteration and species composition. Furthermore, improvements in chemical parameters in many cases will not lead to increases in biological integrity by themselves. Biological monitoring goes beyond the conventional measures of water quality to address questions of ecosystem function and integrity.

Early attempts to apply biological criteria to water quality monitoring were largely qualitative, narrative descriptions based on a single-dimension metric, such as general species richness (Yoder and Rankin 1998). These single-variable measures did not give an adequate understanding of the complex biological interactions in aquatic ecosystems. To address these problems, the biologist James Karr developed the Index of Biotic Integrity (IBI) for freshwater habitats in 1981 (Karr and Chu 1999:2). The goal of the IBI is the integration of data about fish species, populations, and assemblages into a single comparative numeric indicator. Karr's IBI used 12 quantitative metrics based on 3 categories: species richness and composition, trophic composition, and fish abundance and condition. It was first applied to streams and rivers of the midwestern United States.

A number of states in the United States have modified and adjusted the IBI, with Ohio having one of the most comprehensive programs for the assessment of freshwater biological integrity. After seven years of developing its IBI, Ohio formally adopted the index in 1990 and now uses biological monitoring as an established part of its water quality assessment programs (Yoder and Rankin 1995). Ohio's IBI modified some of the original 12 metrics and adjusted them to the state's natural landscape variability (Yoder and Rankin 1995). Whereas the standard IBI concentrates on fish diversity, abundance, and community structure, Ohio has a separate index for invertebrate species, called the Invertebrate Community Index (ICI), which detects additional trends and ecosystem conditions (DeShon 1995).

Less comprehensive but still effective indices have been developed in other states to measure biotic integrity. The Florida Department of Environmental Protection created the Stream Condition Index (SCI) to measure the effects of nonpoint source pollution on biological integrity in the state, using macro-invertebrates as indicator species. The SCI metrics include the total number of taxa, the total number of insect taxa (mayflies, stoneflies, and caddisflies), the number of midge larvae taxa, the percent of dominant taxon, the percent of diptera, the percent of filterers, and the weighted sum of tolerant and intolerant species. With increasing disturbance, species tolerance and richness are expected to decrease, while species composition will change differentially depending on the species. As with other IBIs, the Florida SCI scores reflect these potential changes. State officials continue to modify the SCI (Barbour et al. 1996).

The IBI used in Ohio requires data collection and analysis from hundreds of sites each year, which means that time and money must be spent to obtain IBI scores and recalibrate reference site values. Indices that use macro-invertebrates alone are less expensive because the costs of data collection are not as high for invertebrates as for fish. However, using more than one taxa increases the amount of information available to resource managers. Ohio officials have found, however, that biological surveying is cost-competitive with water chemistry surveys and bioassays (Yoder 1991:101–102). Chemical assessments, for example, have lower unit costs per sample but many more of them are needed. For a single stream in Ohio, chemical assessment in the late 1980s cost up to US$32,400 for 90 samples, compared with US$22,000 for 12 biological surveys. Nine bioassays cost between US$16,000 and US$28,000 (Yoder 1991:101).

Both chemical and biological criteria serve as important components in assessing water quality. Ohio compared biological and chemical assessments in 625 water body segments throughout the state in 1990. In 49.8 percent of the samples, biological impairment was detected with either an IBI or ICI in which no chemical impairment was measured. Both biological and chemical impairment were found in 47.4 percent of the samples, whereas only 2.8 percent of the samples found chemical impairment without any corresponding measured biological degradation. This comparison demonstrated the importance of using biological criteria in addition to chemical indicators of water quality. In a majority of cases in which only biological impairment was measured, the reasons for decreased biological integrity (increased organic matter, habitat modification, siltation) could not be measured using chemical criteria alone (Yoder 1991:98).

A similar approach to evaluating ecosystem conditions that uses whole-watershed metrics rather than site-specific variables within freshwater systems alone is the Watershed Index of Biotic Integrity (W-IBI). This index was developed to evaluate 100 watersheds in the Sierra Nevada Mountains of California (Moyle and Randall 1998:1320). The W-IBI uses such variables as the number of dams, reservoirs, and water diversions, along with the percentage of the area with roads in each watershed to assess condition. Data on native and introduced fish species— as well as on other taxa, such as native frogs, which are highly sensitive to disturbance and have completely disappeared from many watersheds— were also used as indicators. Indices were scored on a scale of 20 to 100, with 80 to 100 being excellent. Only 7 out of 100 watersheds were ranked in the excellent category. Watersheds that scored poorly were those at lower elevations where stream channels had been highly modified by dams, diversions, agriculture, or urbanization, and high-elevation streams where native frogs had declined and introduced predatory fish were present in formerly fishless areas. The W-IBI gives a good watershed-level estimation of biotic integrity and health, but sacrifices some local-level information in the process. For example, within a poorly ranked watershed, there can be streams that have very high biotic integrity, but this will not show up in the W-IBI classification (Moyle and Randall 1998:1323–1325).

The IBI has also been applied outside the United States. For example, an IBI has been developed for the Seine River basin in France (Oberdorff and Hughes 1992). Analysis of these data showed that IBI scores decreased through time, reflecting increasing amounts of pollution and habitat disturbance since the 1960s. IBI values varied longitudinally as well, decreasing in all years in a downstream direction because of an increasing amount of disturbance, a trend that became more marked after 1967.

Another application of the IBI was also used to assess the biological integrity of rivers in India (Ganasan and Hughes 1998) and Mexico (Lyons et al. 1995). The study in India, for example, examined two rivers that had large quantities of untreated waste and toxic heavy metals (Ganasan and Hughes 1998:367). The IBI scores, based on 1986, 1989, and 1991 data, increased downstream from cities and towns, reflecting a gradual recovery of biotic integrity with increasing distance from pollution sources. Nonnative fish species comprised between 4 and 55 percent of individuals at sites where water flow was restricted by an impoundment, compared with 1 to 2 percent of individuals at the least disturbed sites. One of the main conclusions of this study was that the original IBI format could be adapted to Indian rivers, despite an overlap of only two families and no species between the midwestern United States and the Indian study site. However, further evaluations of this trial study need to be undertaken before the Indian IBI can be widely used in an effective and cost-efficient manner (Ganasan and Hughes 1998:378–379).

An alternative to the IBI for making biological assessments of water quality is multivariate statistical analysis of aquatic communities to make predictions of species composition in different sites. Multivariate models have been developed that predict the number of macro-invertebrate freshwater fauna expected to occur at a given site in the absence of environmental stress. The observed invertebrate fauna is then compared to the expected fauna based on statistical methods, and the ratio of observed to expected fauna is used to classify the health of a site. Unstressed sites should have observed/expected ratios that are close to one, whereas stressed sites will have lower ratios.

Examples of freshwater biological monitoring programs that use multivariate statistical methods can be found in the United Kingdom (Wright 1995), Australia (Marchant et al. 1997), and the state of Maine in the United States (Davies et al. 1995). In most cases the sampling strategies used to assess biological communities are the same as those used in IBIs, and the two methods generally produce similar results. Multivariate methods of analysis have the potential to produce accurate predictions of species compositions at unsampled sites based on the correlation between reference site data and measured environmental variables of water quality (Marchant et al. 1997:664).

But more data must be collected than with the IBI to achieve better results.

Condition Indicators of Groundwater Quality

The major sources of groundwater pollution are leaching of pollutants from agriculture, industry, and untreated sewage, saltwater intrusion caused by overabstraction of groundwater (which was discussed in a previous section), and natural hydrogeochemical pollution. Because of the relative inaccessibility and slow movement of the resource, polluted groundwater is very difficult to purify (UNEP 1996:22). Once pollutants enter a groundwater aquifer, the environmental damage can be severe and long lasting, partly because of the very long time needed to flush pollutants out of the aquifer (UNEP 1996:14). Because it is primarily used for drinking water, groundwater pollution from untreated sewage, intensive agricultural, solid waste disposal, and industry can cause serious human health problems (Shiklomanov 1997:42). Global data on the quality of groundwater resources is lacking. Even where available, data usually are not comparable because of the different measures and standards used, which vary by country (Shiklomanov 1997:42; Scheidleder et al. 1999:11; Foster, personal communication, 2000). However, there is evidence that groundwater contamination from fertilizers, pesticides, industrial effluents, sewage, and hydrocarbons is occurring in many parts of the world.

Because the source of groundwater pollution is determined by local conditions, and these vary widely, we have selected particular cases to illustrate pollution problems affecting groundwater resources around the world. The selection of cases is based mostly on data availability. This overview of groundwater quality is by no means comprehensive and portrays trends for only some pollutants and certain regions of the world.

NITRATE POLLUTION

Nitrate pollution of groundwater sources is a problem in both industrialized and industrializing countries (UNEP 1996:28). Nitrate pollution can come from agricultural, urban, or industrial sources; untreated sewage is a major source of nitrate pollution in many parts of the world (UNEP 1996:22). Natural nitrate levels in groundwater are low, usually around 10 mg/l of nitrate (Scheidleder et al. 1999:19). Nitrate moves slowly in soil and groundwater, so there is typically a time lag of 1 to 20 years from the time of pollution until its detection.

In China, nitrogen fertilizer consumption increased sharply in the 1980s and now equals application rates in western Europe. Fourteen cities and counties in northern China, covering an area of 140,000 square kilometers, were sampled to assess the extent of nitrate contamination of groundwater supplies (Zhang et al. 1996: 224). This area had over 20 billion cubic meters of groundwater withdrawals in 1980, mostly for irrigation but with large amounts used for drinking water supplies as well (UN 1997:29). Over one half of the sampled areas had nitrate concentrations that were above the allowable limit for nitrate in drinking water. The majority of these were smaller towns and cities (10,000 to 100,000 in population) that were surrounded by agricultural areas with high fertilizer application rates and that depended on groundwater for the majority of their drinking water supplies (Zhang et al. 1996:227). Pollution of groundwater supplies from synthetic fertilizer application is also a problem in parts of India. Groundwater samples in the states of Uttar Pradesh, Haryana, and Punjab were found to have between 5 and 16 times the prescribed safe amount of nitrate, with one site in Haryana almost 30 times the prescribed limit. Groundwater in these areas is also being progressively depleted because of overabstraction for irrigation (TERI 1998: 214–215).

Nitrate pollution of groundwater supplies is also a problem in industrialized countries, as can be seen from a recent European assessment of groundwater resources (Scheidleder et al. 1999). Twenty-two countries reported regional-level data on nitrate pollution. The number of sampling sites varied widely from one region to another. In 50 of the reported regions, nitrate levels exceeded 25 mg/l in at least a quarter of the total samples. The levels exceeded 25 mg/l in half of the samples in an additional 13 regions. In some regions of France, the Netherlands, and Slovenia, nitrate concentrations exceeded 50 mg/l in 67 percent of sampling sites. In Poland and Moldova, groundwater wells with nitrate concentrations in excess of 45 mg/l could be found across all parts of both countries (Scheidleder et al. 1999:54).

In general, the risk of nitrate pollution for groundwater supplies is directly related to the amount of fertilizers or other nitrogen inputs to the land, and the permeability of the soils through which nitrogen is leached. In the United States, groundwater provides drinking water for more than onehalf of the nation's population (UNEP 1996:12). Data collected by the USGS NAWQA program demonstrate that nitrate concentrations in groundwater exceeding the recommended level of 10 mg/l are significantly greater in aquifers that have high nitrogen inputs and are most vulnerable to leaching (Nolan et al. 1998). Nevertheless, little information exists about groundwater supplies at the national level in the United States, and data are especially poor for ammonium and phosphorous concentrations.

The USGS has begun a more comprehensive program of groundwater quality monitoring, but several more years of sampling will be needed before enough data will be collected to analyze national trends (Mueller and Helsel 1996). A preliminary analysis of nitrate in U.S. groundwater, however, shows that high concentrations in shallow groundwater are widespread and closely correlated with agricultural areas, yet no regional patterns could be discerned (USGS 1999:41). The application rates of synthetic nitrogen fertilizer can be used as a general indicator of groundwater quality because increasing levels of agricultural intensification usually mean overapplication of fertilizers and subsequent leaching into groundwater supplies (Scheidleder et al. 1999:21).

NATURAL (HYDROGEOCHEMICAL) POLLUTION

Natural groundwater contamination in the Indian state of West Bengal and in Bangladesh currently threatens the lives of millions of people. In West Bengal, 7 districts covering an area of over 37,000 square kilometers are contaminated with arsenic, with an estimated 1.1 million people drinking from contaminated wells. A survey found that 200,000 people were suffering from arsenic-related diseases, but the numbers could potentially be much higher because the total population of the affected area is over 9.5 million people (Mandal et al. 1996:976). Naturally occurring arsenic also affects wells across Bangladesh; as many as one million wells in Bangladesh and west Bengal might be contaminated. Ironically, many of these wells were drilled to provide a safe drinking water alternative to heavily polluted surface water supplies. (Nickson et al. 1998: 338).

Capacity of Freshwater Systems to Provide Clean Water

Surface water quality has improved in most OECD countries during the past 20 years, but nitrate and pesticide contamination remain persistent problems. Data on water quality in other regions of the world are sparse, but water quality appears to be degraded in almost all regions with intensive agriculture and rapid urbanization. Unfortunately, little information is available to evaluate the extent to which chemical contamination has impaired freshwater biological functions. However, incidents of algal blooms and eutrophication are widespread in freshwater systems all over the world—an indicator that these systems are profoundly affected by water pollution. In addition, the massive loss of wetlands at a global level has greatly impaired the capacity of freshwater systems to filter and purify water.

Nitrate pollution of groundwater supplies in northern China and India is likely to remain a serious problem for years to come. Increasing populations mean that agricultural productivity has to increase to meet growing needs, yet in China the amount of arable land is slowly decreasing due to urbanization. It is estimated that application rates for nitrogen fertilizer will double or triple in the next 30 years (Zhang et al. 1996: 223). Not only are there negative health effects associated with nitrate pollution of groundwater, but overapplication has serious economic costs as well. For one 115,000-hectare region in the northern province of Shaanxi, economic losses because of excessive application of nitrogen fertilizer were estimated to be US$13 million (Emteryd et al. 1998:443).

Water Quality Information Status and Needs

Because the quality of water is one of the most critical factors affecting the quality of life on Earth, monitoring water quality is an urgent and important task. Unfortunately, there have been few sustained programs for the global monitoring of the quality of water, with the result that information is highly localized and far from complete.

One of the only global attempts at water quality monitoring has been the UNEP GEMS/WATER program that examined data from 82 major river basins worldwide over a period of a decade and a half. This program gathered data on a variety of water quality issues, including nutrients, oxygen balance, suspended sediments, salinization, microbial pollution, and acidification. Yet, the number of monitored watersheds were too sparse and the frequency and type of measurements were too inconsistent to paint a comprehensive picture of global water quality trends. Further studies of this kind need more comprehensive and systematic data collection, and monitoring should be carried out indefinitely so that long-term trends can be analyzed. Data needs are especially critical for developing countries, which often do not have strong national monitoring programs, yet, face serious water quality problems.

Surface water monitoring programs are relatively well developed in most OECD countries, where many different physical and chemical measures are monitored. Data for groundwater are less reliable in most cases, and much more information needs to be gathered in all countries on groundwater quality. Even in the United States, efforts by the USGS to monitor groundwater quality have begun only in recent years, and current monitoring covers only a portion of the country's land area.

In developing countries, the situation is much worse. There are a few localized studies of groundwater quality for many developing countries, but no country has a comprehensive program for groundwater monitoring. A global program for addressing groundwater quality issues could be built around a few indicator variables that are most likely to adversely affect human health (such as nitrates, salts, and toxic chemicals), with frequent monitoring carried out in areas of heavy dependence on groundwater use.

One of the most important issues that must be addressed in any global program of water quality monitoring is the need for more biological monitoring. It has been shown that chemical monitoring alone fails to identify many instances in which freshwater ecosystems are stressed or threatened by nonchemical factors. Declines of biological integrity can have adverse effects on human welfare as well, through declining fish and shellfish stocks. Biological monitoring is needed to give greater information about overall ecosystem health and integrity.

However, unlike programs for the monitoring of chemical and physical parameters, biological monitoring cannot easily be carried out on a global scale. This is because the information needed to conduct useful indicators of biological integrity cannot be found in single-measure indices. Information about freshwater biotic integrity is highly dependent on local circumstances, such as the numbers and types of organisms and the ways in which freshwater biological communities are structured. No single IBI-type measure could be constructed for the entire world because IBIs require locally calibrated reference sites to be useful. Unlike conventional chemical measures of water quality, biological indices are difficult to construct even at the national level, depending on the size of the country. In the United States, where several nationwide programs for measuring chemical aspects of water quality are underway, biological monitoring is conducted at the state level, and it probably will never be coordinated at a higher level of administration.

One of the biggest challenges in future global water monitoring programs is the integration of chemical and biological measures of water quality. Although the former can be carried out at national and even continental scales, the latter must be approached at the local and regional level. Yet, both have important messages to tell us about water quality and ecosystem health.