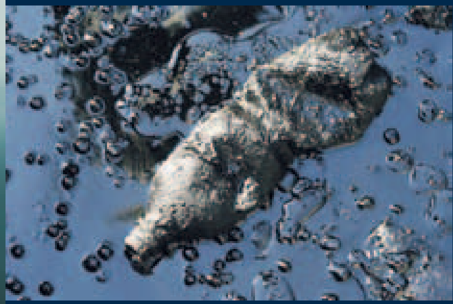
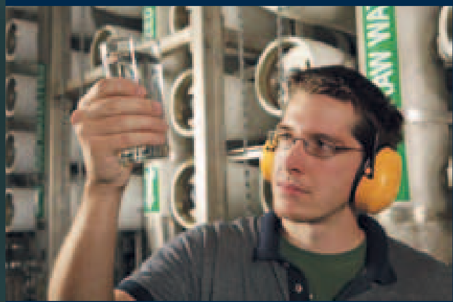
UNEP

Clearing the Waters

A focus on water quality solutions





Authors
Meena Palaniappan
Peter H. Gleick
Lucy Allen
Michael J. Cohen
Juliet Christian-Smith
Courtney Smith
Editor: Nancy Ross

Designer
Nikki Meith

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Pacific Institute
654 13th Street
Preservation Park
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www.pacinst.org

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ACKNOWLEDGMENTS

This publication represents the collective expertise of a diverse group of individuals concerned with protecting our very limited freshwater resources and preserving their fundamental role in maintaining human and ecosystem health. These experts have applied their collective wisdom to produce a report which offers practical, effective solutions to counter the catastrophic degradation of the Earth's freshwater ecosystems. It urges the international community, governments, communities and households to act responsibly and cooperatively to build a brighter future. It is hoped that the contents of this document, developed as a contribution to World Water Day 2010 celebrations on the theme -- Water Quality, will inspire all who read it to contribute to this important cause.

UNEP gratefully acknowledges the efforts of the many contributors to this document, whose hard work and insight were essential to its completion. UNEP greatly appreciates the enormous contribution of Peter H. Gleick, Meena Palaniappan, Lucy Allen, Juliet Christian-Smith, Michael J. Cohen, Courtney Smith and editor Nancy Ross of the Pacific Institute, USA, who produced the publication under tight timeframes. The advice offered by Jeffrey Thornton, of the Southeastern Wisconsin Regional Planning Commission (USA) is also gratefully acknowledged, as is the work by Iwona Wagner of the UNESCO IHP-VI Project on Ecohydrology (Poland) who peer-reviewed the publication in detail.

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The hard work and perseverance of all these individuals have made the preparation of this publication possible, and sincere thanks go to all of them.

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FOREWORD

It was the English poet W. H Auden who said many have lived without love, none without water: A sentiment that underlines the half way point of the new decade for action under the simple but poignant theme 'Water is Life'.

The challenge of water in the 21st century is one of both quantity and quality. This publication is about the quality dimension of that equation, highlighting the links between clean water and public health and the health of the wider environment.

The fact is that, often as a result of mismanagement, much of the water that is available in developing but also developed economies is polluted and contaminated to varying levels.

In some places that contamination – whether from sources such as industrial or raw sewage discharges – is so acute that it can be deadly, triggering water-related diseases that take millions of lives annually often among the young and the vulnerable.

Contaminated river systems, coastal waters and other ecosystems are not only a health risk, they are also a risk to livelihoods and economies if they can no longer, for example, support healthy fisheries.

The purpose of this report, *Clearing the Waters*, is to re-focus the attention of the international community on the critical role that freshwater quality plays in meeting human, environmental, and development commitments, including those of the Millennium Development Goals (MDGs).

It is to also underline the inordinate opportunities for addressing water quality issues through improved management of this most precious of precious resources.

Part of a comprehensive response includes educating and engaging both the public and policymakers and enlisting the scientific community in order to make the links between the wider economy, human activity and water quality.

This report is designed to provide a road map for engaging the international and national communities, in order to catalyze change.

2010 comes five years after the launch of the new decade for action and five years before the international community promised to meet the MDGs.

Framing a response to the challenge of water quality, internationally and nationally, will be key to whether we can claim success in 2015 across many if not all of those poverty related goals.

This report is launched as a contribution to the MDGs but also to the wider sustainability challenges facing six billion people, rising to nine billion by 2050 whose future will be largely defined by how we manage the natural and nature-based resources of the planet.

Achim Steiner
United Nations Under-Secretary General and
Executive Director, United Nations Environment Programme

EXECUTIVE SUMMARY

Every day, millions of tons of inadequately treated sewage and industrial and agricultural wastes are poured into the world's waters. Every year, lakes, rivers, and deltas take in the equivalent of the weight of the entire human population– nearly seven billion people – in the form of pollution. Every year, more people die from the consequences of unsafe water than from all forms of violence, including war. And, every year, water contamination of natural ecosystems affects humans directly by destroying fisheries or causing other impacts on biodiversity that affect food production. In the end, most polluted freshwater ends up in the oceans, causing serious damage to many coastal areas and fisheries and worsening our ocean and coastal resource management challenges.

Clean, safe, and adequate freshwater is vital to the survival of all living organisms and the smooth functioning of ecosystems, communities, and economies. But the quality of the world's water is increasingly threatened as human populations grow, industrial and agricultural activities expand, and as climate change threatens to cause major alterations of the hydrologic cycle. Poor water quality threatens the health of people and ecosystems, reduces the availability of safe water for drinking and other uses, and limits economic productivity and development opportunities. There is an urgent need for the global community – both the public and private sector – to join together to take on the challenge of protecting and improving the quality of water in our rivers, lakes, aquifers, and taps. To do so we must commit to preventing future water pollution, treating waters that are already contaminated, and restoring the quality and health of rivers, lakes, aquifers, wetlands, and estuaries; this enables these waters to meet the broadest possible range of human and ecosystem needs. These actions will be felt all the way from the headwaters of our watersheds to the oceans, fisheries, and marine environments that help sustain humanity.

Water quality challenges

A wide range of human and natural processes affect the biological, chemical, and physical characteristics of water, and thus impact water quality. Contamination by pathogenic organisms, trace metals, and human-produced and toxic chemicals; the introduction of non-native species; and changes in the acidity, temperature, and salinity of water can all harm aquatic ecosystems and make water unsuitable for human use.

Numerous human activities impact water quality, including agriculture, industry, mining, disposal of human waste, population growth, urbanization, and climate change. Agriculture can cause nutrient and pesticide contamination and increased salinity. Nutrient enrichment has become one of the planet's most widespread water quality problems (UN WWAP 2009), and worldwide, pesticide application is estimated to be over 2 million metric tonnes per year (PAN 2009). Industrial activity releases about 300-400 million tons of heavy metals, solvents, toxic sludge, and other waste into the world's waters each year (UN WWAP Water and Industry). About 700 new chemicals are introduced into commerce each year in the United States alone (Stephenson 2009). Mining and drilling create large quantities of waste materials and byproducts and large-scale waste-disposal challenges.

Widespread lack of adequate disposal of human waste leads to contamination of water – worldwide, 2.5 billion people live without improved sanitation (UNICEF and WHO 2008), and over 80 percent of the sewage in developing countries is discharged untreated in receiving water bodies (UN WWAP 2009). Meanwhile, growing populations will potentially magnify these impacts, while climate change will create new water quality challenges.

Water quality impacts

Water contamination weakens or destroys natural ecosystems that support human health, food production, and biodiversity. Studies have estimated that the value of ecosystem services is double the gross national product of the global economy, and the role of freshwater ecosystems in purifying water and assimilating wastes has been valued at US$ 400 billion (2008$) (Costanza et al. 1997). Freshwater ecosystems are among the most degraded on the planet, and have suffered proportionately greater species and habitat losses than terrestrial or marine ecosystems (Revenga et al. 2000). Most polluted freshwater ends up in the oceans, damaging coastal areas and fisheries.

Every year, more people die from the consequences of unsafe water than from all forms of violence, including war – and the greatest impacts are on children under the age of five. Unsafe or inadequate water, sanitation, and hygiene cause approximately 3.1 percent of all deaths – over 1.7 million deaths annually – and 3.7 percent of DALYs (disability adjusted life years) worldwide (WHO 2002). Livelihoods such as agriculture, fishing, and animal husbandry all rely on water quality as well as quantity. Degraded water quality costs countries in the Middle East and North Africa between 0.5 and 2.5 percent of GDP per year (WB 2007), and economic losses due to the lack of water and sanitation in Africa alone is estimated at US$ 28.4 billion or about 5 percent of GDP (UN WWAP 2009). Women, children, and the economically disadvantaged are the most affected by water quality impacts. Over 90 percent of those who die as a result of water-related diseases are children under the age of 5. Women are forced to travel long distances to reach safe water. And the poor are often forced to live near degraded waterways, and are unable to afford clean water.

Moving to solutions and actions

Effective solutions to water quality challenges exist and have been implemented in a number of places. It is time for a global focus on protecting and improving the quality of the world's freshwater resources. There are three fundamental solutions to water quality problems: (1) prevent pollution; (2) treat polluted water; and (3) restore ecosystems.

Focus on pollution prevention

Pollution prevention is the reduction or elimination of contaminants at the source before they have a chance to pollute water resources – and it is almost always the cheapest, easiest, and most effective way to protect water quality. Pollution prevention strategies reduce or eliminate the use of hazardous substances, pollutants, and contaminants; modify equipment and technologies so they generate less waste; and reduce fugitive releases and water consumption. Pollution prevention will also require better design of human settlements to improve water infiltration and reduce non-point source pollution. As the world takes on the challenge of improving water quality, pollution prevention should be prioritized in international and local efforts.

Expand and improve water and wastewater treatment

Many water sources and watersheds are already of poor quality and require remediation and treatment. Both high-tech, energy-intensive technologies and low-tech, low-energy, ecologically focused approaches exist to treat contaminated water. More effort to expand the deployment of these approaches is needed; they need to be scaled up rapidly to deal with the tremendous amount of untreated wastes entering into waterways every day; and water and wastewater utilities need financial, administrative, and technical assistance to implement these approaches.

Restore, manage, and protect ecosystems

Healthy ecosystems provide important water quality functions by filtering and cleaning contaminated water. By protecting and restoring natural ecosystems, broad improvements in water quality and economic well-being can occur. In turn, ecosystem protection and restoration must be considered a basic element of sustainable water quality efforts.

Mechanisms to achieve solutions

Mechanisms to organize and implement water quality solutions include: (1) better understanding of water quality through improved monitoring; (2) more effective communication and education; (3) improved financial and economic tools; (4) deployment of effective methods of water treatment and ecosystem restoration; (5) effective application and enforcement of legal and institutional arrangements; and (6) political leadership and commitment at all levels of society.

Improve understanding of water quality

Ongoing monitoring and good data are the cornerstones of effective efforts to improve water quality. Addressing water quality challenges will mean building capacity and expertise in developing countries and deploying real-time, low-cost, rapid, and reliable field sampling tools, technologies, and data-sharing and management institutions. Resources are needed to build national and regional capacity to collect, manage, and analyze water quality data.

Improve communication and education

Among the most important tools for solving water quality problems are education and communication. Water plays key cultural, social, economic, and ecological roles. Demonstrating the importance of water quality to households, the media, policy makers, business owners, and farmers can have a tremendous impact in winning key improvements. A concerted global education and awareness-building campaign around water quality issues is needed, with targeted regional and national campaigns that connect water quality to issues of cultural and historical importance.

Use effective legal, institutional, and regulatory tools

New and improved legal and institutional frameworks to protect water quality are needed from the international level down to the watershed and community level. As a first step, laws on protecting and improving water quality should be adopted and adequately enforced. Model pollution-prevention policies should be disseminated more widely, and guidelines should be developed for ecosystem water quality as they are for drinking water quality. Planning at the watershed scale is also needed to identify major sources of pollution and appropriate interventions, especially when watersheds are shared by two or more political entities. Standard methods to characterize in-stream water quality, international guidelines for ecosystem water quality, and priority areas for remediation need to be developed and deployed globally.

Deploy effective technologies

Many effective technologies and approaches are available to improve water quality through pollution prevention, treatment, and restoration that range from ecohydrology


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approaches to conventional treatment. A focus on deploying approaches to collect, transport, and treat human wastes and industrial and agricultural water is critically important. This will require a focus on connecting communities, governments, and businesses to effective water quality technologies and approaches, developing new technologies when needed to meet specific environmental or resource needs, and providing technical, logistical, and financing support to help communities and governments implement projects to improve water quality.

Improve financial and economic approaches

Many water quality problems are the result of inadequate access to financing to develop water-treatment or restoration programmes, or from inappropriate pricing and subsidy programmes. Better understanding of the economic value of maintaining ecosystem services and water infrastructure is required, as are more effective water-pricing systems that permit sufficient cost recovery, ensure adequate investments, and support sustainable long-term operation and maintenance. Innovative regulatory approaches and standards are needed, for example, to entail payments for ecosystem services or to require polluters to internalize the costs of pollution.

Moving forward: clean water for today and tomorrow

Water has always been at the center of healthy ecosystems and human societies, yet the freshwater resources on which we all depend are becoming increasingly polluted. As a global community, we need to refocus our attention on improving and preserving the quality of our water. The decisions made in the next decade will determine the path we take in addressing the global water quality challenge. That challenge requires bold steps internationally, nationally, and locally to protect water quality. Directing local, national, and international priorities, funding, and policies to improve water quality can ensure that our global water resources can once again become a source of life. *Clean* water is life. We already have the know-how and skills to protect our water quality. Let us now have the will. Human life and prosperity rest on our actions today to be the stewards, not polluters, of this most precious resource.

INTRODUCTION

The quality of water is central to all of the roles that water plays in our lives. From the beauty of natural waterways teeming with wildlife, to the vital livelihoods that clean rivers and streams support, to the essential role that safe water plays in drinking water and health – good water quality is fundamental to the network of life and livelihood that water supports.

Water is the source of life on earth, and human civilizations blossomed where there was reliable and clean freshwater. Use of water by humans – for drinking, washing, and recreation – requires water free from biological, chemical, and physical sources of contamination. Plants, animals, and the habitats that support biological diversity also need clean water. Water of a certain quality is needed to grow food, to power cities, and to run industries.

Water quality is as important as water quantity for satisfying basic human and environmental needs, yet it has received far less investment, scientific support, and public attention in recent decades than water quantity, even though the two issues are closely linked. As part of the effort to improve water quality, the United Nations Environment Programme (UNEP) is supporting educational efforts around the world to call attention to water quality challenges and solutions. This summary assessment is part of those efforts and synthesizes existing data from many public databases and published reports.

Part 1 of the report provides an overview of current major water quality contaminants and the human activities that affect water quality. Part 2 details the impacts that poor water quality has on the environment, human health, and vulnerable communities, and quantifies the economic costs of poor water quality. Part 3 of the report offers insights into specific solutions available to address water quality problems, and Part 4 explores the wide range of mechanisms through which the solutions can be achieved. Part 5 details key recommendations to improve and protect water quality for the international community, national governments, communities and households.

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I. Overview of current water quality challenges

Contaminants in water

Both human activities and natural activities can change the physical, chemical, and biological characteristics of water, and will have specific ramifications for human and ecosystem health. Water quality is affected by changes in nutrients, sedimentation, temperature, pH, heavy metals, non-metallic toxins, persistent organics and pesticides, and biological factors, among many other factors (Carr and Neary 2008). Following are brief discussions of these major contaminants.

Many contaminants combine synergistically to cause worse, or different, impacts than the cumulative effects of a single pollutant. Continued inputs of contaminants will ultimately exceed an ecosystem's resilience, leading to dramatic, non-linear changes that may be impossible to reverse (MA 2005a). For example, the extinction of all 24 species of fish endemic to the Aral Sea resulted from dramatic increases in salinity as inflows of freshwater dropped. While some still hold out hope that it may be possible to restore Aral Sea salinity to previous levels, there is no way to reverse the extinction events that occurred. Another example of such threshold-type changes is the creation of toxic algal blooms (see Lake Atitlán case study, below), with direct and indirect economic impacts on local populations.

Nutrients

Nutrient enrichment has become the planet's most widespread water quality problem (UN WWAP 2009). Most often associated with nitrogen and phosphorus from agricultural runoff, but also caused by human and industrial waste, nutrient enrichment can increase rates of primary productivity (the production of plant matter through photosynthesis) to excessive levels, leading to overgrowth of vascular plants (e.g. water hyacinth), algal blooms, and the depletion of dissolved oxygen in the water column, which can stress or kill aquatic organisms. Some algae (cyanobacteria) can produce toxins that can affect humans, livestock, and wildlife that ingest or are exposed to waters with high levels of algal production. Nutrient enrichment can also cause acidification of freshwater ecosystems, impacting biodiversity (MA 2005b). Over the long term, nutrient enrichment can deplete oxygen levels and eliminate species with higher oxygen requirements, such as many species of fish, affecting the structure and diversity of ecosystems (Carpenter et al. 1998). Some lakes and ponds have become so hypereutrophic (nutrient rich and oxygen poor) due to nutrient inputs that all macro-organisms have been eliminated.

Erosion and sedimentation

Erosion is a natural process that provides sediments and organic matter to water systems. In many regions, human activities have altered natural erosion rates and greatly altered the volume, rate, and timing of sediment entering streams and lakes, affecting physical and chemical processes and species' adaptations to pre-existing sediment regimes. Increased sedimentation can decrease primary productivity, decrease and impair spawning habitat, and harm fish, plants, and benthic (bottom-dwelling) invertebrates. Fine sediments can attract nutrients such as phosphorus and toxic contaminants such as pesticides, altering water chemistry (Carr and Neary 2008). Dams and other infrastructure can dramatically degrade a stream's natural sediment transport function, starving downstream reaches of needed nutrient and chemical inputs. For example, the construction of major dams on the Yangtze River has had a noticeable impact on sediment load reaching the East China Sea according to Chinese scientists. In recent years, sediment reaching Datong, near the Yangtze's delta, dropped to only 33 percent of the

1950-1986 levels (Xu et al. 2006). Among the consequences of this drop in sediment are growing coastal erosion and a change in the ecological characteristics and productivity of the East China Sea (Xu et al. 2006).

Water temperature

Water temperature plays an important role in signaling biological functions such as spawning and migration, and in affecting metabolic rates in aquatic organisms. Altering natural water temperature cycles can impair reproductive success and growth patterns, leading to long-term population declines in fisheries and other classes of organisms. Warmer water holds less oxygen, impairing metabolic function and reducing fitness. Such impacts can be especially severe downstream of thermal or nuclear power generation facilities or industrial activities, where the return of water to the streams may be substantially warmer than ecosystems are able to absorb (Carr and Neary 2008).

Acidification

The pH of different aquatic ecosystems determines the health and biological characteristics of those systems. A range of industrial activities, including especially mining and power production from fossil fuels, can cause localized acidification of freshwater systems. Acid rain, caused predominantly by the interaction of emissions from fossil-fuel combustion and atmospheric processes, can affect large regions. Acidification disproportionately affects young organisms, which tend to be less tolerant of low pH. Lower pH can also mobilize metals from natural soils, such as aluminum, leading to additional stresses or fatalities among aquatic species. Acidification is widespread, especially downwind of power plants emitting large quantities of nitrogen and sulfur dioxides, or downstream of mines releasing contaminated groundwater. According to the US Environmental Protection Agency, for example, more than 90 percent of the streams in the Pine Barrens, a wetlands region in the eastern United States, are acidic as a result of upwind energy systems, particularly coal-fired power plants (US EPA 2009a).

Salinity

Freshwater plant and animal species typically do not tolerate high salinity. Various actions, often but not exclusively anthropogenic, can cause salts to build up in the water. These include agricultural drainage from high-salt soils, groundwater discharge from oil and gas drilling or other pumping operations, various industrial activities, and some municipal water-treatment operations. Additionally, the chemical nature of the salts introduced by human activities may differ from those occurring naturally; for example, there

may be higher ratios of potassium than sodium salts. Rising salinity can stress some freshwater organisms, affecting metabolic function and oxygen saturation levels. Rising salinity can also alter riparian and emergent vegetation, affect the characteristics of natural wetlands and marshes, decrease habitat for some aquatic species, and reduce agricultural productivity and crop yields (Carr and Neary 2008).

Pathogenic organisms

One of the most widespread and serious classes of water quality contaminants, especially in areas where access to safe, clean water is limited, is pathogenic organisms: bacteria, protozoa, and viruses. These organisms pose one of the leading global human health hazards. The greatest risk of microbial contamination comes from consuming water contaminated with pathogens from human or animal feces (Carr and Neary 2008). In addition to microorganisms introduced into waters through human or animal fecal contamination, a number of pathogenic microorganisms are free-living in certain areas or are, once introduced, capable of colonizing a new environment. These free-living pathogens, like some *Vibrio* bacterial species and a few types of amoebas, can cause major health problems in those exposed, including intestinal infections, amoebic encephalitis, amoebic meningitis, and occasional death (WHO 2008). Viruses and protozoa also pose human health risks, including *Cryptosporidium* and *Giardia*, Guinea worm, and others.

Trace metals

Trace metals, such as arsenic, zinc, copper, and selenium, are naturally found in many different waters. Some human activities like mining, industry, and agriculture can lead to an increase in the mobilization of these trace metals out of soils or waste products into fresh waters. Even at extremely low concentrations, such additional materials can be toxic to aquatic organisms or can impair reproductive and other functions. In the early 1980s, high concentrations of selenium in agriculture drainage water discharged to the Kesterson National Wildlife Refuge in California extirpated all but one species of fish and caused widespread bird die-offs, as well as severe deformities in several bird species (Ohlendorf 1989).

Human-produced chemicals and other toxins

Diverse human-produced organic chemicals can enter surface and groundwater through human activities, including pesticide use and industrial processes, and as breakdown products of other chemicals (Carr and Neary 2008). Many of these pollutants, including pesticides and other non-metallic toxins, are used globally, persist in the environment, and can be transported long ranges to regions where they have never been produced (UNEP 2009).

Organic contaminants (sometimes called "persistent organic pollutants", or POPS), such as certain pesticides, are commonly found to be contaminating groundwater by leaching through the soil and surface waters through runoff from agricultural and urban landscapes. DDT, a pesticide that has been banned in many countries but is still used for malaria control in countries throughout Africa, Asia, and Latin America (Jaga and Dharmani 2003), remains persistent in the environment and is resistant to complete degradation by microorganisms (WHO 2004a). Even in countries where DDT has been banned for decades, it is still consistently found in sediments, waterways, and groundwater. For some of these materials, non-lethal doses may be ingested by invertebrates and stored in their tissues, but as larger organisms consume these prey species, the amounts of pesticides and other materials bioaccumulate, eventually to toxic levels. Some pesticides break down in the environment over time, but breakdown products may also be toxic and can concentrate in sediments, to be released in large volumes during scouring events or other disturbances.

Other organic pollutants, such as dioxins, furans, and polychlorinated biphenyls (PCBs) are the byproduct of industrial processes and enter the environment both through their use and disposal (UNEP 1998). Such materials have become an emerging threat, with possible long-term degradation of freshwater and other ecosystems. PCB contamination has been widespread around the world. In New York, for instance, over a million pounds (over 550 metric tonnes) of PCBs were dumped into the Hudson River in the mid-20th century. High PCB levels found in Hudson River fish led to bans on fishing, and decades of remediation efforts that continue to this day (US EPA 2009b).

Other emerging contaminants (addressed in more detail below) include endocrine disruptors, pharmaceuticals, and personal care products that may not be removed by existing wastewater treatment operations and end up entering freshwater systems. These contaminants can impair reproductive success in birds and fish and feminize male offspring, and they may have other impacts yet to be detected.

Introduced species and other biological disruptions

The rising incidence of invasive species displacing endemics and altering water chemistry and local foodwebs increasingly affects freshwater systems and should be considered a water quality problem (Carr and Neary 2008). Aquatic species have in many cases been introduced deliberately into distant ecosystems for recreational, economic, or other purposes. In many instances, these introductions have decimated endemic fish and other aquatic organisms, and they can also degrade local watersheds. Other species have invaded inadvertently, transported on the hulls of recreational watercraft or in the bilgewater of commercial boat traffic. For example, invasive species such as zebra (*Dreissena polymorpha*) and quagga (*D. bugensis*) mussels have devastated local ecosystems, altering nutrient cycles and pushing endemic species to the brink of extinction. Mussels in particular also pose grave threats to human infrastructure, clogging pumps and intakes and choking canals, leading to costly and continual maintenance challenges.

In South Africa, invasive plant species have altered local water quality and reduced water quantity as well by increasing evapotranspiration rates in watersheds. According to the South African Department of Water Affairs and Forestry, invasive alien species are causing billions of rands of damage to the country's economy every year, and are the single biggest threat to the country's biodiversity. Since its inception in 1995, the Working for Water Programme has cleared more than one million hectares of invasive alien plants while also providing jobs and training to approximately 20,000 people from among the most marginalized sectors of society per annum (SA DWAF 2009). In the United States, the invasion of some species of mussels has led to additional costs exceeding a billion dollars annually to the water power industry and in impacts on local ecosystems (De Leon 2008).

Emerging contaminants

A growing number of contaminants are being detected in water for two reasons: new chemicals are being introduced for agricultural, industrial, and household use and can enter and persist in the environment, and new testing techniques allow contaminants to be detected at lower and lower levels. Substances can enter the environment through intentional, measured releases (pesticide applications); as regulated or unregulated industrial and agricultural by-products; through accidental spills or leaks during the manufacturing and storage of these chemicals; or as household waste (Carr and Neary 2008). In agricultural settings, over-spraying and long-range transport can cause these substances to be found long distances from the initial point of application.

About 700 new chemicals are introduced into commerce each year in the United States alone (Stephenson 2009), and worldwide, pesticide application is estimated to be approximately 5 billion pounds (over 2 million metric tonnes) (PAN 2009). Despite their widespread use, the prevalence, transport, and fate of many of these new chemicals remain largely unknown because until recently, testing techniques were unable to detect contaminants at the low concentrations at which they are present in the environment (Carr and Neary 2008).

Synthetic chemicals known as endocrine disruptors are an excellent example of emerging contaminants where the threats and consequences for water quality, human health, and the environment are still not fully understood. Endocrine disruptors – chemicals that can interfere with hormone action – have been identified among chemicals used in agriculture, industry, and households, and for personal care, including pesticides, disinfectants, plastic additives, and pharmaceuticals like birth control pills. Many of these endocrine-disruptors mimic or block other hormones in the body, disrupting the development of the endocrine system and the organs that respond to endocrine signals in organisms indirectly exposed during early developmental stages; these developmental effects are permanent and irreversible (Colborn 1993). The effects of endocrine disruptors on wildlife include the thinning of eggshells in birds, inadequate parental behavior, cancerous growths, and other effects (Carr and Neary 2008). For example, the feminization of fish living downstream from wastewater treatment plants has long been linked to estrogenic pharmaceuticals (Sumpter 1995) and new studies have also linked feminization of amphibians to endocrine disrupting pesticides such as atrazine (Hayes et al. 2006).

The effects of these chemicals on humans and human development are less well known; however, animal studies suggest there is cause for concern, even at low doses. In addition, research shows the effects may extend beyond the exposed individual, particularly affecting fetuses of exposed pregnant women and breastfed children. Recent reports also show multi-generation effects of some endocrine disruptors, through modification of genetic materials and other heritable mechanisms (ES 2009).

Pharmaceuticals and personal care products are also of increasing concern. These chemicals originate from products like cosmetics, toiletries, and detergents, as well as from pharmaceuticals ranging from painkillers and antidepressants to hormone-replacement therapies and chemotherapy agents (Carr and Neary 2008). These chemicals enter the environment and waterways as wastewater facilities are not equipped to remove them (Carr and Neary 2008). While the low concentrations currently present in waterways do not present any observable acute health effects, they may present subtle behavioral and reproductive problems for humans and wildlife (Carr and Neary 2008), and there are likely synergistic impacts when combined with other endocrine disruptors. As an example, at concentrations of micrograms/L of the antibiotic tetracycline one study found measurable negative impacts on aquatic bacteria (Verma et al. 2007). New research is needed to address these uncertainties.

In addition to emerging chemical contaminants, there is also the threat of emerging pathogens – those that are appearing in human populations for the first time, or have occurred before but are increasing in incidence or are expanding into areas where they have not been reported (WHO 2003a). Not only do water-related diseases remain a leading cause of global morbidity and mortality, but several studies have confirmed that the variety of disease is expanding and the incidence of many water-related microbial diseases is increasing (WHO 2003a).

Pathogens can emerge as a result of new environments or changes in environmental conditions, like dams and irrigation projects; from the use of new technologies; and from scientific advancements, such as the inappropriate use of antibiotics, insecticides, and pesticides creating resistant pathogen strains (WHO 2003a). In recent years, 175 species of infectious agents from 96 different genera have been classified as emerging pathogens (WHO 2003a). The emergence of new pathogens or the increase in their incidence also threatens water quality.

Human activities that affect water quality

A wide range of human activities affect water quality. Below, four major categories are discussed – agricultural production, industrial and mining activities, water infrastructure, and the direct disposal of untreated or partly treated human wastes into water systems – along with the impacts these activities have on water quality. There are also key processes that have and will continue to impact water quality: these are population growth, urbanization, and climate change. These are described below.

Agriculture

The vast extent of agricultural activities around the world contributes significantly to both economic productivity and

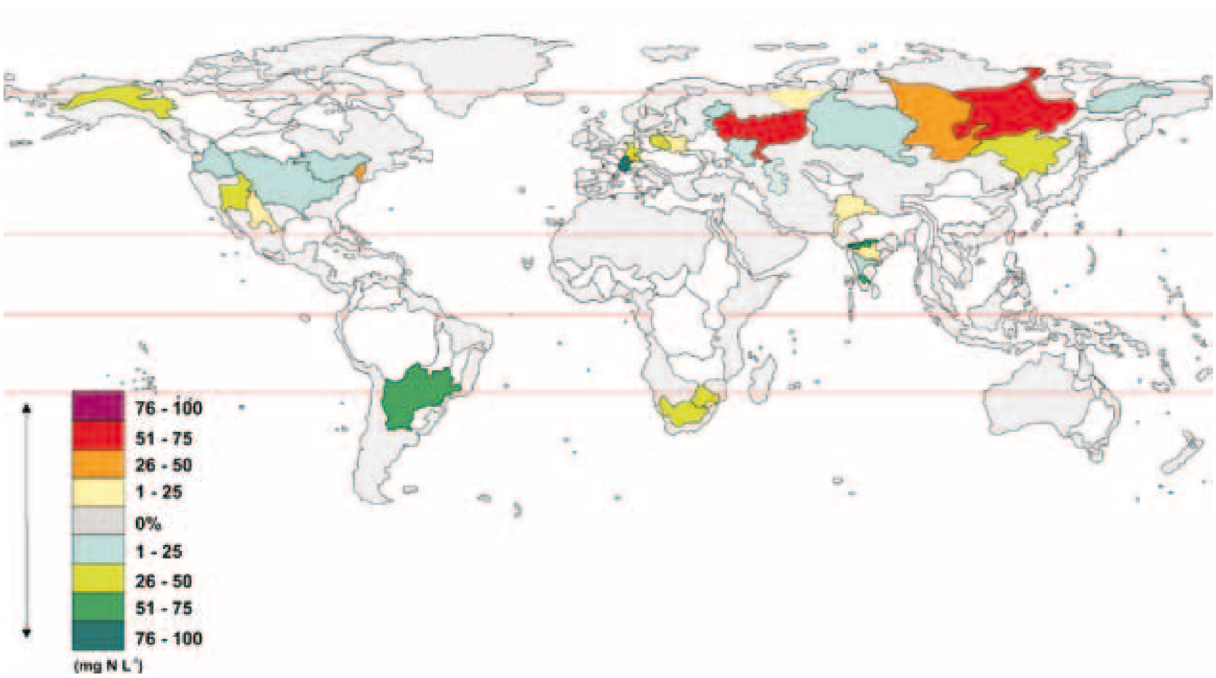

Figure 1. Changes in nitrogen concentrations for significant global watersheds by region for the periods 1990-1999 and 2000-2007. *Source: UNEP 2008*

water-pollutant loads. Since the 1970s, there has been growing concern over the increases in nitrogen, phosphorus, and pesticide runoff into surface and groundwater. Intensive cultivation and growing concentrations of "factory" livestock or aquaculture operations have also long been known to produce large non-point source contributions of pollutants to surface and groundwater pollution (Ignazi 1993). A comparison of domestic, industrial, and agricultural sources of pollution from the coastal zone of Mediterranean countries found that agriculture was the leading source of phosphorus compounds and sediment (UNEP 1996a). Furthermore, nitrate is the most common chemical contaminant in the world's groundwater and aquifers (Spalding and Exner 1993). According to various surveys in India and Africa, 20-50 percent of wells contain nitrate levels greater than 50 milligrams per liter, and in some cases as high as several hundred milligrams per liter (cited in FAO 1996). Recent data from UNEP GEMS/Water shows that mean nitrate concentrations have increased in the last decade in watersheds in the Americas, Europe, Australasia, and most significantly, in Africa and the eastern Mediterranean (Figure 1).

Beyond nitrate contamination, agricultural activities are also linked to the salinization of surface water, eutrophication (excess nutrients), pesticides in runoff, and altered erosion and sedimentation patterns. The Food and Agriculture Organization (FAO 1996) has compiled a summary of common agricultural impacts on surface water and groundwater resources (Table 1).

Industry and energy production

Industrial activities are a significant and growing cause of poor water quality. Industry and energy production use accounts for nearly 20 percent of total global water withdrawals (UN WWAP 2009), and this water is typically returned to its source in a degraded condition. Wastewater from industrial facilities such as power plants, paper mills, pharmaceutical manufacturers, semiconductor fabrication plants, chemical plants, petroleum refineries, and bottling facilities, and processes such as mining and drilling, all contribute to poor water quality around the world. Industrial wastewater can contain a number of different pollutants, including:

- Microbiological contaminants like bacteria, viruses, and protozoa;
- Chemicals from industrial activities like solvents and organic and inorganic pesticides, polychlorinated biphenyls (PCBs), asbestos, and many more;
- Metals such as lead, mercury, zinc, copper, and many others;

Table 1. Agricultural impacts on water quality. *Modified from FAO 1996.*

Agricultural activity	Impacts	
	Surface water	Groundwater
Tillage/ploughing	Sediment/turbidity: sediments carry phosphorus and pesticides adsorbed to sediment particles; siltation of river beds and loss of habitat, spawning ground, etc.	Soil compaction can reduce infiltration to the groundwater system.
Fertilizing	Runoff of nutrients, especially phosphorus, leading to eutrophication causing taste and odor in public water supply; excess algal growth leading to deoxygenation of water and fish kills.	Leaching of nitrate to groundwater; excessive levels are a threat to public health.
Manure spreading	Carried out as a fertilizer activity; spreading on frozen ground results in high levels of contamination of receiving waters by pathogens, metals, phosphorus, and nitrogen leading to eutrophication and potential contamination. In addition, manure application can spread antibiotics and other pharmaceutical products that are given to livestock.	Contamination of groundwater, especially by nitrogen
Pesticides	Runoff of pesticides leads to contamination of surface water and biota; dysfunction of ecological system in surface waters by loss of top predators due to growth inhibition and reproductive failure; public health impacts from eating contaminated fish. Pesticides are carried as dust by wind over very long distances and contaminate aquatic systems thousands of miles away (e.g. tropical/subtropical pesticides found in Arctic mammals).	Some pesticides may leach into groundwater causing human health problems from contaminated wells.
Feedlots/animal corrals	Contamination of surface water with many pathogens (bacteria, viruses, etc.) leading to chronic public health problems. Also contamination by metals, antibiotics, and other pharmaceuticals contained in urine and faeces.	Potential leaching of nitrogen, metals, etc. to groundwater.
Irrigation	Runoff of salts leading to salinization of surface waters; runoff of fertilizers and pesticides to surface waters with ecological damage, bioaccumulation in edible fish species, etc. High levels of trace elements such as selenium can occur with serious ecological damage and potential human health impacts.	Enrichment of groundwater with salts, nutrients (especially nitrate).
Clear cutting	Erosion of land, leading to high levels of turbidity in rivers, siltation of bottom habitat, etc. Disruption and change of hydrologic regime, often with loss of perennial streams; causes public health problems due to loss of potable water.	Disruption of hydrologic regime, often with increased surface runoff and decreased groundwater recharge; affects surface water by decreasing flow in dry periods and concentrating nutrients and contaminants in surface water.
Silviculture	Broad range of effects: pesticide runoff and contamination of surface water and fish; erosion and sedimentation problems.	Soil compaction limits infiltration.
Aquaculture	Release of pesticides and high levels of nutrients to surface water and groundwater through feed and faeces, leading to serious eutrophication.	

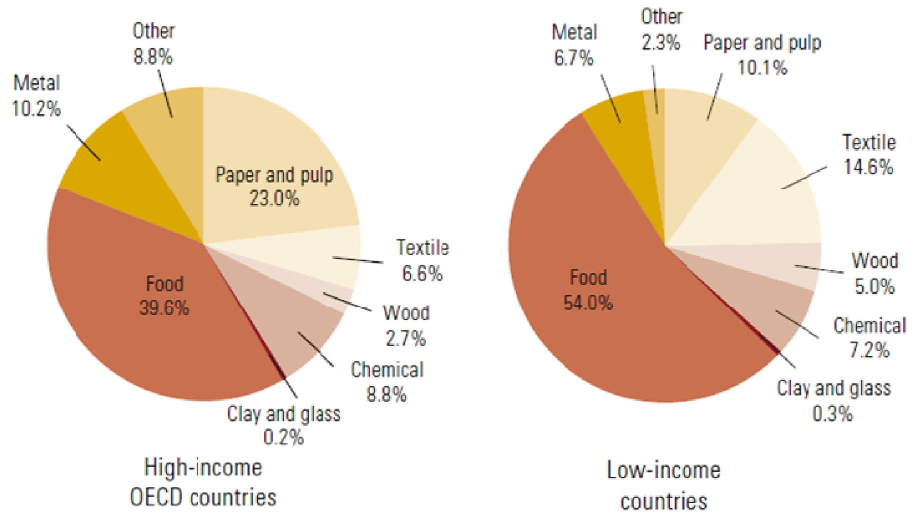

Figure 2. Contribution of main industrial sectors to the production of organic water pollutants. *Source: UN WWAP 2003, using data from World Bank 2001.*

- Nutrients such as phosphorus and nitrogen;
- Suspended matter including particulates and sediments;
- Temperature changes through the discharge of warm cooling-water effluent;
- Pharmaceuticals and personal care products.

The production of energy also has significant impacts on water quality (see Table 2 below), mostly because of the vast quantities of water required for power-plant cooling and the extensive risk of contamination during the search for and production of fossil fuels. There are three major impacts of concern: (1) the production of vast quantities of contaminated groundwater during the drilling of oil and gas wells; (2) the withdrawal of water for power plant cooling that reduces water available for ecosystems; and (3) the heating and subsequent discharge of cooling water, which raises the ambient water temperature in rivers, streams, and lakes, with effects on natural ecosystems. Some wastewater is also produced by certain power plants, with concomitant impacts on water quality.

Worldwide, it is estimated that industry is responsible for dumping 300-400 million tons of heavy metals, solvents, toxic sludge, and other waste into waters each year (UN WWAP Water and Industry). The amount of industrial water pollution in different countries varies greatly, based both on the amount of industrial activity in the country and the types of pollution-prevention and water-treatment technologies used by industrial facilities.

In many developed nations, significant progress has been made in reducing direct discharges of pollutants into water bodies, primarily through increased treatment of industrial wastewater before it is discharged. An OECD report found that in member countries in the past several decades, “industrial discharges of heavy metals and persistent chemicals have been reduced by 70-to-90 percent or more in most cases” (OECD 2006). In developing countries, on the other hand, more than 70 percent of industrial wastes are not treated before being discharged into water (UN-Water Statistics). Still, developed nations often discharge more industrial pollution into water bodies on a per-capita basis than less developed nations (see Figure 3 below), and contamination of water-bodies can occur even when industrial wastewater undergoes some treatment, because chemicals released by industrial processes are often not treatable in conventional wastewater treatment plants. For example, chlorinated solvents were found in 30 percent of groundwater supplies in 15 Japanese cities, sometimes traveling as much as 10 km from the source of pollution (UNEP 1996b).

Industrial water pollution is a major source of damage to ecosystems and human health throughout the world (see sections on ‘Effects of poor water quality on ecosystems’ and ‘Effects of poor water quality on human health’, below). Many industrial contaminants also have grave consequences for human health when consumed as part of drinking water.

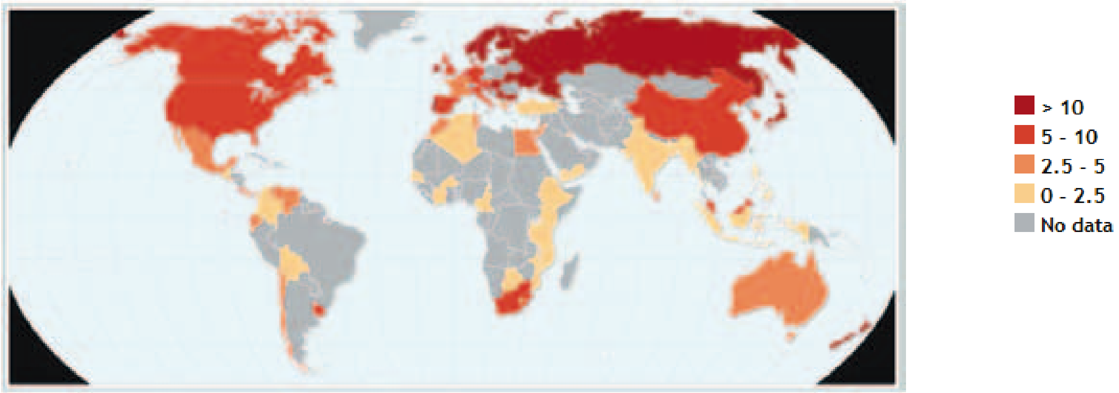

Figure 3. Discharge of industrial water pollution (in metric tons per million people per day). *Reprinted by permission of Marian Koshland Science Museum of the National Academy of Sciences (www.koshland-science.org) Safe Drinking Water is Essential (www.drinking-water.org)*

And they can alter broad water quality characteristics, such as temperature, acidity, salinity, or turbidity of receiving waters, leading to altered ecosystems and higher incidence of water-borne diseases. Impacts can be heightened by synergistic effects among mixtures of contaminants.

Mining

Mining activities have long been known to cause significant water quality impacts. Mining and drilling for fossil fuels bring to the surface materials long buried in the earth, including water. They also tend to generate large quantities of waste materials or byproducts relative to the target resource, creating large-scale waste disposal challenges. Additionally, surface water may drain into mine openings, and groundwater frequently accumulates in mines. Mine drainage waters can be extremely polluted by salts in the groundwater itself; metals such as lead, copper, arsenic, and zinc present in the source rock; sulfur compounds leached from rock; and mercury or other materials used in extraction and processing. The pH of these drainage waters can be dramatically altered. Some mine drainage is extremely acidic, with a pH of 2-3; other source materials can lead to very alkaline discharges. These contaminated drainage waters can devastate local waterways, eliminating fish and rendering streams unfit for human use. In the U.S. state of Colorado alone, some 23,000 abandoned mines have polluted 2,300 kilometers of streams (Banks et al. 1997).

In areas where environmental regulations are less stringent or are not vigorously enforced, degradation of water quality by such operations can be substantial. In countries with more aggressively enforced regulations, problems still arise from treatment and containment methods that have since proven ineffective, such as unlined "evaporation pits" for contaminated mine drainage that allow contaminants to infiltrate into the local groundwater. Additionally, there are tens of thousands of historic mines – many abandoned for more than a hundred years – that continue to discharge toxic metals and acid drainage into local waterways.

Mining wastes can cause significant ecological destruction. Often, solid mine wastes are dumped into streams, destroying habitat and causing siltation and heavy metal and other contamination. Even when such wastes are stored out of water channels, trace materials can leach into surface waters and infiltrate into local groundwater. Fine-grained tailings can wash into local waterways and degrade streams by covering and filling coarser-grained substrates. Such sedimentation increases stream turbidity, decreasing net primary productivity and smothering the eggs of fish and other aquatic organisms, and it can alter stream flow dynamics.

The pace of urbanization is increasing globally, putting more pressure on local water quality. According to the United Nations, global urban population rose from 13 percent in 1900 to 29 percent in 1950, to 49 percent in 2005. The UN predicts that the proportion of people living in urban areas by 2030 will rise to 60 percent (UN 2006). In addition to discharges of urban and industrial wastewater, urban areas add to poor water quality in a number of ways. The high concentration of impervious surfaces increases runoff from roads and can carry numerous pollutants such as oils, heavy metals, rubber, and other automobile pollution into waterways and streams. The reduction in water percolation into the ground can also affect the quantity and quality of groundwater, and stormwater runoff can overwhelm wastewater treatment systems when high volume flows exceed treatment capacities.

Table 2. Connections between the energy sector and water quality. *Modified from US DOE 2006*

Energy process	Connection to water quality
Energy extraction and production	
Oil and gas exploration	Impact on shallow groundwater quality
Oil and gas production	Produced water can impact surface and groundwater
Coal and uranium mining	Tailings and drainage can impact surface water and groundwater
Electric power generation	
Thermoelectric (fossil, biomass, nuclear)	Thermal and air emissions impact surface waters and ecology
Hydro-electric	Can impact water temperatures, quality, ecology
Solar PV and wind	None during operation, minimal water use for panel and blade washing
Refining and processing	
Traditional oil and gas refining	End-use can impact water quality
Biofuels and ethanol	Refinery wastewater treatment
Synfuels and hydrogen	Wastewater treatment
Energy transportation and storage	
Energy pipelines	Wastewater requires treatment
Coal slurry pipelines	Final water is poor quality, requires treatment
Barge transport of energy	Spills or accidents can impact water quality
Oil and gas storage caverns	Slurry disposal impacts water quality and ecology

Water-system infrastructure

All human-built systems can lead to the introduction of non-native species; altered water quality (nutrients, oxygen, temperature); changes in system dynamics (flow size, duration, and timing); and the ability of ecosystems to flourish. Water-supply infrastructure, including irrigation systems and dams, affect water quality through a number of mechanisms. These impacts are sometimes classified as follows (WCD 2000):

- First-order impacts that involve modifying the physical, chemical, and geomorphological characteristics of a river and streamflow, including altering the natural quantity, distribution, and timing;
- Second-order impacts that involve changes in the biological productivity and characteristics of riverine ecosystems and downstream habitats such as wetlands and deltas; and
- Third-order impacts that involve alterations to flora or fauna (such as fish, amphibians, or birds) caused by a first-order effect (such as blocking migration or destruction of spawning habitat) or a second-order effect (such as changes in temperature, decrease in the availability of a food source, or mobilization of a contaminant). Third-order impacts can also include effects on human health, industrial or agricultural productivity, or even politics.

Water-related infrastructure imposes many changes on natural water systems. Large dams built for water storage, recreation, or flood control are intended to alter the natural hydrologic regime by affecting the size, distribution, and timing of streamflow. They also trap sediments and food sources used downstream in deltas, and affect temperature regimes leading to changes in ecosystems. Major irrigation systems withdraw water from rivers or lakes to be used consumptively on fields to grow food, reducing flows in natural systems. These physical, chemical, and geomorphological changes affect the biological productivity and characteristics of aquatic ecosystems, which in turn affect flora and fauna as well as economics and politics.

A classic example of a water system severely affected by human development is the Aral Sea, fed by the Amu Darya and Syr Darya. The Aral Sea was once the fourth largest inland body of water in the world, after Lake Superior, supporting 24 unique species of fish and a large fishing population. The Soviet Union built a series of dams and irrigation systems to divert river flows in order to grow cotton on around 3 million hectares of new farmland, but these massive freshwater withdrawals (first order impacts) led to the shrinking of the Sea and a corresponding increase in salinity (second order impacts). By 2000, the Sea had shrunk to one-fourth of its original size and all 24 species of endemic fish had gone extinct (third order impacts). Pollutants and dust from the exposed seabed have also caused significant public health problems in local populations.

Many major world rivers are so heavily modified that their original ecosystems are disappearing, along with fish, amphibian, and bird populations they used to support. The Colorado River in the United States and Mexico now has dams that can hold five years of average annual runoff and almost the entire flow is allocated to human urban and agricultural uses in the U.S. and Mexico. The impacts on water quality of this extensive development include: most original fish species are extinct or threatened with extinction, riparian vegetation has been fundamentally modified due to the elimination of flushing and scouring flows now moderated by dams, the temperature regime of the river is very different than the original system, and political relations between the U.S. and Mexico are increasingly influenced by water issues. The Orange-Vaal River in South Africa has 24 dams of various sizes and a severely modified temperature and sediment regime (WCD 2000), and many other examples exist of comparable modification of riverine systems by water infrastructure.

Uncontrolled disposal of human wastes

A major activity that leads to widespread water quality problems is the disposal of human waste. Fecal contamination often results from the discharge of raw sewage into natural waters – a method of sewage disposal common in developing countries, and even in more advanced countries like China, India, and Iran (Carr and Neary 2008). Even in developed countries, partially or inadequately treated sewage remains a major source of water quality contamination.

Lack of adequate sanitation contaminates water courses worldwide and is one of the most important forms of global water pollution. Worldwide, 2.5 billion people live without improved sanitation (UNICEF and WHO 2008). Over 70 percent of these people, or 1.8 billion people who lack sanitation, live in Asia. The amount of fecal coliform bacteria (associated with fecal matter) detected in Asia's rivers is 50 times the WHO guidelines, indicating a high level of dangerous microbial contaminants (UNEP 2000). In Asia, and in countries around the world, these pathogenic microbes can be introduced into drinking water from unsafe or inadequate water treatment, leading to a wide range of serious health threats.

Of the world's regions, sub-Saharan Africa moved forward the slowest in achieving improved sanitation: only 31 percent of residents had access to improved sanitation in 2006. Even improved sanitation does not guarantee the protection of water quality; often there is no wastewater treatment to protect water bodies from receiving collected sewage. Over 80 percent of the sewage in developing countries is discharged untreated in receiving water bodies (UN WWAP 2009).

Open defecation poses an extreme human health risk and significantly compromises quality in nearby water bodies. Eighteen percent of the world's population, or 1.2 billion people, defecate in the open (UNICEF and WHO 2008). Over a billion people, or one out of every three people who live in rural areas, defecate in the open. In Southern Asia, 63 percent of rural people – 778 million people – practice open defecation. Fecal coliform, an important marker to gauge the extent of contamination with human or animal sewage, indicates the failure of adequate sanitation and wastewater treatment, and also the existence of pathogens. UNEP GEMS/Water provides in their Global Water Quality Outlook an assessment of the extent of fecal contamination downstream of major cities, which can be found in Figure 4.

Population growth, urbanization, development

The United Nations estimates that by 2050, the world population will surpass 9 billion people – an increase by nearly half of the 2000 population, with most of the growth occurring in developing countries. In addition, the world is becoming increasingly urban, with the majority of the world's current population living in urban areas (UN 1999). Most of this growth and increase in urbanization will occur in developing countries that already suffer from water stress. Growing populations, especially when concentrated in urban settings, can create more domestic waste and sewage that can overload streams and treatment systems, leading to even more polluted waters. It is estimated that 42 percent of water used for domestic and municipal purposes is returned to the water cycle, accounting for 11 percent of total wastewater. In some countries, as little as 2 percent of total sewage volumes are treated. In developing countries,

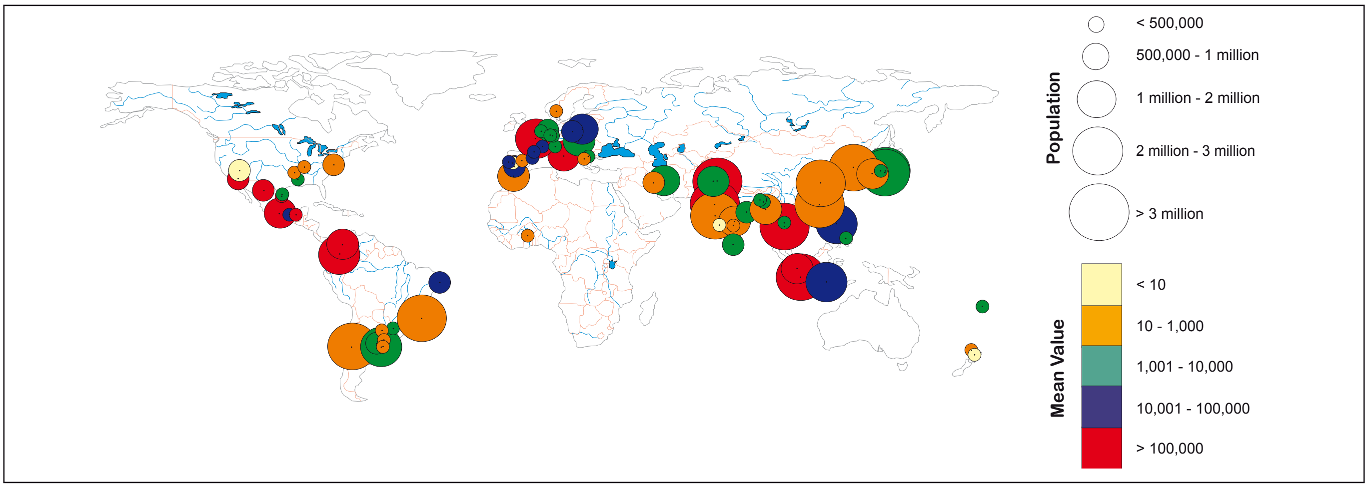

Figure 4. Fecal coliform concentrations (No./100ml MF) at river monitoring stations near major cities. *Source: UNEP GEMS/Water 2007.*

investments in water-treatment facilities are constantly unable to keep up with population growth, leaving most wastewater untreated.

In addition to the creation of more wastewater, urban areas add to poor water quality in a number of ways. The high concentration of impervious surfaces increases runoff from roads and can carry numerous pollutants such as oils, heavy metals, rubber, and other automobile pollution into waterways and streams. The reduction in water percolation into the ground can also affect the quantity and quality of groundwater. Stormwater runoff in urban areas can overwhelm combined stormwater and wastewater treatment systems when high volume flows exceed treatment capacities.

With more people, there will be a need for increased agricultural productivity. Enlargements in irrigated areas, coupled with an increased reliance on and use of fertilizers and pesticides in developing countries, will lead to increases in polluted irrigation return flows. Deforestation will increase as more cropland and wood for fuel are needed, accelerating erosion and leaching and increasing water pollution. In most developing countries, efforts at pollution control, if they exist, cannot keep up with population growth and urbanization. Increased human demand can lead to groundwater overdraft, which can cause soil subsidence, and in coastal areas, can cause salt-water intrusion. Many development projects undertaken to provide water security, like irrigation systems and dams, introduce other problems, including impacts on human health, disruption of local ecosystems, and decline of local economies (UN 1994).

Because per capita income in urban areas is greater and the costs of water quality improvements are potentially smaller due to higher densities, it is possible that urbanization may provide opportunities to implement water quality improvements.

Climate change

Climate change has a major impact on the world's freshwater resources, water quality, and water management (Pachauri and Reisinger 2008, Bates et al. 2008). Increases in water temperature and changes in the timing and amount of runoff are likely to produce unfavorable changes in surface-water quality, which will in turn affect human and ecosystem health. The threats posed by climate change will serve as an additional stressor to many already degraded systems, particularly those in developing countries.

Global surface temperatures are rising, and there is evidence that the rate of warming is accelerating. By 2100, current climate models project that rising greenhouse-gas concentrations will "likely" increase global mean surface air temperature between 1.1˚C and 6.4˚C relative to a 1980-1999 baseline (Meehl et al. 2007).[1] Water temperature is an important determinant of surface-water quality, as it controls the types of aquatic life that can survive, regulates the amount of dissolved oxygen in the water, and influences the rate of chemical and biological reactions. As a result, higher surface-water temperatures from climate change will accelerate biological productivity, increase the amount of bacteria and fungi in the water, and promote algal blooms (Kundzewicz et al. 2007). These algal blooms, some of

[1] Terms such as "likely" and "very likely" have a very specific meaning associated with the expected probability of occurrence, given current knowledge. A "likely" outcome has more than a 66 percent probability of occurrence. A "very likely" outcome has more than a 90 percent probability of occurrence.

which can create toxins that pose serious risks to human and ecosystem health (Chorus and Bartram1999), will be promoted further by increases in nutrient concentrations in water due to human activities (such as agriculture and urbanization, described above) (Jabobs et al. 2001).

Over the next 100 years, climate models suggest that warmer temperatures will very likely lead to greater climate variability and an increase in the risk of hydrologic extremes, i.e., floods and droughts. Perhaps the most significant and likely impact is a change in the timing of runoff in watersheds with large amounts of winter snowfall as higher temperatures lead to an increase in the ratio of rain to snow, faster snowmelt runoff, and earlier loss of snow. Many regions may see an increase in the intensity of precipitation events, which will likely result in increasing sedimentation and leaching of solid mine wastes, among other off-stream contaminants. However, in areas that are projected to become drier, the increase in intensity will be offset by a reduction in the frequency of precipitation events (Meehl et al. 2007). Increased drought conditions in these regions are likely to both concentrate pollutants and lead to growing water scarcity.

In regions that will experience increases in precipitation, more runoff will present its own water quality challenges. Pollutants associated with human activity, including pesticides, heavy metals, and organic matter, may flow into surface water faster and with less time for natural water filtration and groundwater infiltration (Kundzewicz et al. 2007). However, in some regions, this same increase in water flow could potentially dilute these contaminants, improving water quality (Carr and Neary 2008). In addition, with global warming, forests and agriculture will migrate northward, increasing pollutant and nutrient loads to northern aquatic ecosystems. Not only will the production of pollution increase, but with potentially less water available to dilute them, pollutants can become even more concentrated.

Both increased flooding from more intense rainfall, along with periodic storm surges intensified by rising sea levels due to climate change, may affect water quality, overloading infrastructure, such as stormwater drainage operations, wastewater systems, treatment facilities, mine tailing impoundments, and landfills, which can increase the risk of contamination (Jacobs et al. 2001). Extreme rainfall will also increase the threat of water-borne diseases (Confalonieri et al. 2007), as standing water can turn into breeding grounds for disease-carrying insects and microbial pathogens (Carr and Neary 2008). Many diarrheal diseases, such as cholera, *Cryptosporidium*, *E. coli*, *Giardia*, shigella, typhoid, and viruses such as hepatitis A reach their height during rainy seasons (WHO 2009). But drought also increases the risk of diarrheal disease (WHO 2009): areas that suffer from lack of water are at increased risk for diarrheal and other water-related diseases because low water levels do not dilute waste as well, leading to higher concentrations of pathogens (Confalonieri et al. 2007). This is of particular concern in developing countries where the biological quality of water is poor due to lack of sanitation and water treatment (Kundzewicz et al. 2007).

Variation in precipitation will also affect the salinity levels of surface water. Increased rainfall or runoff will likely reduce salinity levels, especially in winter, while lower precipitation levels and higher temperatures during summertime could increase salinity levels (Jacobs et al. 2001). As a result, semi-arid regions that suffer from decreasing runoff will be greatly impacted by salinization (Jacobs et al. 2001). Exacerbating the problem in these regions, human activities to combat hotter, drier climates, such as increased irrigation, can further worsen salinization (Confalonieri et al. 2007).

Coastal regions, particularly small islands, will be especially impacted by an increase in salinization. If surface waters that empty into the ocean, such as estuaries and inland reaches, suffer from a decrease in their stream flow, more saline ocean water can penetrate further upstream (Kundzewicz et al. 2007). The quality of groundwater is also affected by salinization. Groundwater pumping from coastal aquifers, when increased to meet the demands of a growing population and increased development, can reduce the recharge of the aquifer, and seawater can more readily intrude. A rise in sea level will further accelerate sea-water intrusion into coastal aquifers and affect coastal ecosystems and drinking water supplies (Jacobs et al. 2001, Burns 2002).

Limited research has been done to identify relevant water quality and ecosystem parameters for understanding climate-change impacts (Albert 2008), or to understand climate change impacts in association with other stressors. It is important that this data collection be done now, so that baselines can be developed and adaptation efforts can be based on good data.

Finally, water quality will be affected, both positively and negatively, by the decisions society makes in the face of climate change. Water-management decisions, such as building large-scale hydropower dams and utilizing wastewater reuse on crops, have implications for local and regional water quality, and ecosystem and human well-being. With scarce water supplies combined with increased human use, there is a need to manage the allocation of water, often requiring greater transboundary management and collaboration.


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II. Impacts of poor water quality

Effects of poor water quality on the environment

Freshwater ecosystems are among the most degraded on the planet by worsening water quality and quantity (UN WWAP 2009). They have suffered proportionately greater species and habitat losses than terrestrial or marine ecosystems, from factors that will likely grow worse in coming years (Revenga et al. 2000). In addition to irreversible species loss, impaired water quality reduces the economic value of services provided by freshwater systems, including their ability to treat and clean water for human uses and to provide important habitat for aquatic species.

Rivers and Streams

At any one time, an estimated 2,000 km^3 of the world's freshwater flows in river and streams, a scant 0.006 percent of the planet's total freshwater reserves and less than 3 percent of the freshwater found in the world's lakes. These resources are not distributed uniformly: 31 percent of total annual global runoff occurs in Asia and 25 percent occurs in South America, while only 1 percent occurs in Australia (Shiklomanov 1993). Yet rivers and streams claim a vastly disproportionate influence on the landscape and on global biodiversity. More than two-thirds of terrestrial species may use streams and their associated riparian corridors at some point in their lives (Naiman et al. 1993). Surface waters generally supply almost half of the world's drinking water supply and 20 percent of the world's electricity (UN WWAP 2009).

Despite humanity's reliance on flowing water, human activities have severely degraded the quantity and quality of rivers and streams worldwide, diminishing their ability to provide valuable ecosystem services and driving species to extinction. Factors as diverse as nutrient enrichment from agricultural runoff and domestic wastes, acid mine drainage, invasive species, dams, and diversions have radically altered rivers and streams across the planet, from the smallest ephemeral tributaries to the world's largest rivers. Sixty percent of the world's 227 biggest rivers have interrupted stream flows due to dams and other infrastructure (UN WWAP 2003). Interruptions in stream flow dramatically decrease sediment and nutrient transport to downstream stretches, reducing water quality and impairing ecosystem health. Widespread water quality problems degrade ecosystem services, imposing costs on local populations and governments. For example, more than 90 percent of China's rivers are polluted, prompting a commitment from the Chinese government to invest US$ 13.5 billion in wastewater treatment infrastructure and other pollution control projects (Li 2009).

Physical, chemical, and biological factors such as geology, precipitation, temperature, and fauna and flora are shaped by rivers. Differences in these factors across river basins frustrate efforts to generalize descriptions of rivers' ability to absorb pollutants or prescriptions for rehabilitation and restoration. The tremendous variability in the type, magnitude, and timing of human activities across river basins further challenges efforts to generalize. For example, the discharge of effluent into a river with a fairly constant flow might be naturally remediated, while the discharge of the same volume and quality of effluent into another river with the same average annual flow but greater seasonal variability or differences in physical chemistry or biodiversity could create significant adverse impacts.

The Cuyahoga River (see case study below) offers an excellent example of the impacts of pollution on a river, as well as cause for optimism for the ability to rehabilitate degraded rivers.

Lakes

The world's lakes contain an estimated 91,000 km^3 of fresh water, about 1 percent of the planet's estimated fresh groundwater reserves and less than 0.5 percent of water frozen in glaciers and the ice caps (Shiklomanov 1993), but the vast majority of the planet's accessible fresh water. Lakes differ from rivers and other surface water systems in many respects, most notably in the time that water and other substances remain in the system (known as retention or residence time). This affects lakes' ability to remediate pollutants and contributes to their complex dynamics (WLVARC 2007). Lakes provide many valuable ecosystem services, provisioning both food and water, buffering flood flows, and supporting extensive biodiversity. Many lakes have high degrees of endemism, meaning that some species are found there and nowhere else on the planet. Lakes support transportation, recreation, and other cultural amenities (WLVARC 2007).

Lakes are also vulnerable to a wide range of water quality threats, including increased salinity, changes in temperature, and contamination by industrial and agricultural chemicals. For example, excessive nutrients can lead to eutrophication – the over-productivity of organisms in water – leading to the creation of algal blooms and the depletion of oxygen concentrations, which threatens many animal and plant species (Carr and Neary 2008). Cyanobacterial blooms (which together with algae form a group of organisms called phytoplankton) pose human health threats, as the cyanobacteria often release toxins, many of which are some of the most toxic substances known. These toxins have a range of health effects, including damage to the nervous system and liver, tumor promotion, and even death (Duy et al. 2000). Merely swimming or coming into contact with water contaminated with dangerous levels of these cyanobacteria can make animals and humans sick; children are particularly vulnerable due to their small size.

Groundwater

Groundwater provides valuable provisioning and regulating ecosystem services. Some 30 percent of the world's freshwater stocks are found underground, supplying drinking water for an estimated two billion people and irrigation for an estimated 40 percent of the world's food. Many groundwater

Case study

Cuyahoga River

Where: Northern Ohio, United States
Length: 160 km
Watershed: 2,100 km^2
Mean Discharge: 25 m^3/sec, 0.79 km^3/year

The Cuyahoga, a relatively small river in northern Ohio, U.S.A., carries great historic and symbolic importance as it flows from its headwaters some 160 km, through the cities of Akron and Cleveland, to discharge into Lake Erie. For more than one hundred years, it received un- and under-treated industrial and domestic wastes, at times including those from rendering plants, steel mills, and chemical plants, leaving the river a lifeless, toxic sewer. A national news magazine described it as the river that "oozes rather than flows" (Time 1969).

The oily sludge floating atop the river reportedly caught fire for the first time in 1868. Another fire in 1912 spread and killed five dockworkers; a major fire in 1952 caused a reported US$ 12 million (2009) in damages. On June 22, 1969, the river again caught fire, for at least the ninth time in a century. This time, however, the event was captured on national television and led to calls for major reform of U.S. water quality laws. The municipal and state governments contested jurisdiction and authority, but new national attention on this and other water pollution disasters pressured the federal government to enact sweeping new legislation and centralize authority. In 1970, the new Environmental Protection Agency (EPA) was formed. In 1972, the federal Clean Water Act was enacted, requiring that waterways should become "fishable and swimmable."

By a two-to-one margin, voters in Cleveland approved a large bond issue in late 1968 to build a wastewater treatment plant, new sewer lines, and to improve existing facilities, vastly expanding the city's capacity to treat effluent and capture stormwater flows. In the past 40 years, local industries and the regional wastewater utility have spent US$ 3.5 billion to control and reduce water pollution. EPA enforcement of new laws decreased dumping of raw wastes into the river. Forty years later, the Cuyahoga supports more than 60 species of fish and birds and mammals have returned to the river's banks, and the quality of Lake Erie (which receives Cuyahoga River flows) is also vastly improved (Time 1969, Maag 2009, Rose 2009).

Case study

Lake Atitlán

Where: Guatemala
Key fact: Oligotrophic terminal lake
Elevation 1,562 m
Surface Area: 130 km^2
Watershed: 580 km^2
Depth: Average 220 m, Max ~340 m

Lake Atitlán, a terminal lake ringed by volcanoes high in the mountains of central Guatemala, was known for its stunning beauty. The lake provided food and fiber to many communities along its shores and attracted Guatemalan and international tourists. To promote additional tourism, local officials stocked the lake with non-native black bass (*Micropterus* spp.) in the late 1950s. The introduced bass devastated the lake's fragile ecosystem and have been implicated in the extinction of the endemic Atitlán grebe (*Podilymbus gigas*).

Recently, the lake's clear waters have been obscured by noxious algal blooms, at times reportedly extending over more than 4,500 hectares of the lake's surface. Toxic cyanobacteria have been identified at the lake, endangering human health. Experts have warned residents not to have any contact with the lake's water, threatening drinking water security for local towns.

The toxic cyanobacteria proliferated in the presence of excessive nutrients, especially phosphorus, that run off from fertilized fields in the basin and from the detergent used to wash clothes on the shoreline. Healthy ecosystems do not exhibit such infestations, but the introduced bass disrupted the lake's natural resilience and eliminated natural controls. Population pressures and rising deforestation in the basin have degraded the land's ability to filter and modulate nutrients into the lake, exacerbating the problem.

The Guatemalan government recently announced a US$ 350 million plan that includes construction of sewage treatment plants in adjacent communities, an effort to convert farmers to organic farming, and a public and tourist education campaign, in an effort to rehabilitate the lake (Fieser 2009).

systems act to filter and attenuate pollutants, especially microbial contaminants (Morris et al. 2003).

By virtue of its location, groundwater typically enjoys greater protection from pollutants than do surface waters, though several contaminants degrade groundwater and diminish its utility. Because of the slow movement of contaminants and subsurface water, it may take years for a contaminant plume to pollute a groundwater source. This slow movement and the fact that groundwater and subsurface contaminants are not readily detected also challenge efforts to determine and control pollution sources. Once contaminated, groundwater is difficult and expensive to remediate (UNEP 1996b). Global data on groundwater quality are very limited, due to the cost of monitoring and analysis (Revenga et al. 2000).

Salinization has become an important threat to groundwater quality, especially in coastal areas where groundwater extraction at unsustainable rates has led to seawater intrusion. In Chennai, India, overextraction of groundwater has resulted in saline groundwater nearly 10 km inland of the sea (UNEP 1996b), and similar problems can be found in populated coastal areas around the world. Sea-level rise due to climate change is also expected to impact coastal aquifer quality by increasing sea-water intrusion. Certain irrigation practices can also increase groundwater salinity and can increase nitrate and pesticide leaching, increasing costs for drinking water suppliers and for irrigators (Morris et al. 2003). In some areas, most notably Bangladesh, natural factors contaminated groundwater supplies with elevated levels of arsenic, impairing human health (see case study for more information).

Coastal zones

Water pollution is often of particular concern in coastal zones. Nations around the world, particularly developing economies in tropical regions, often have an especially high concentration of industry and population along their coasts. Because of this, water pollution and the subsequent impacts on the environment and local communities are highly concentrated in those areas as well. Common sources of this pollution in coastal zones include industrial waste, urban waste, land construction, dam development, mangrove conversion, coral mining, and canalization in wetlands (UN WWAP 2009).

These activities can be extremely destructive to both freshwater and marine habitats. As the end point of most river systems, coastal zones receive much of the water pollution in rivers as it accumulates over the course of a river. Cities or areas of high industrial activity often lead to large amounts of untreated sewage and industrial waste flowing into the sea, destroying fisheries and leading to substantial public health impacts for fishers and bathers. Many of the most polluting marine activities (e.g., fishing, oil extraction, etc.) typically take place in the coastal zone (which contains 80 percent of marine biomass) (UNESCO 1996). Furthermore, the interactions of marine and freshwater systems in coastal zones often concentrate the pollution from both systems into this one zone.

The impacts of this pollution can be severe. Not only does it lead to massive destruction to ecosystems and habitats, but it affects humans who rely on these ecosystems for their livelihoods and leads to substantial human health problems, especially among the young and tourists who have not developed immunity to endemic diseases found in these waters (ENHIS 2007). The United Nations Industrial Development Organization (UNIDO) has begun work to reduce these impacts by sharing good environmental practices with key developing industries and providing technical assistance for implementing Integrated River Basin Management (IRBM) and Integrated Coastal Zone Management (ICZM) in emerging economies (UN WWAP 2009).

Vegetated wetlands

As opposed to the open waters of rivers and lakes, marshes, fens, bogs, swamps, and peatlands can be characterized by the presence of specific types of emergent vegetation and may have no open water at all. Such wetlands encompass the transition between terrestrial and aquatic ecosystems (Mitch and Gosselink 2000). Differences in classification hamper efforts to estimate the total share of the world's freshwater resources in such vegetated wetlands; Shiklomanov (1993) lists the water volume of "swamps" at 11,500 km^3; other sources simply include such waters within other categories (Gleick 1993).

Wetlands provide several critical ecosystem services. They filter and improve water quality; attenuate and moderate flood water flows; provide a natural replenishment function for groundwater, recharging underlying aquifers; and support extensive biodiversity. In parts of the world, more than half of such wetlands have disappeared completely, as their water sources have been diverted or as they have been converted to agricultural uses or developed for other purposes (Mitch and Gosselink 2000). For example, conversion of portions of the Yala Swamp in western Kenya to agriculture threatens to diminish the value of several important ecosystem services provided to local populations, including provision of water for drinking and transportation, fish for food and commerce, and various materials for construction (Schuyt 2005).

Other wetlands have been degraded by excessive volumes of contaminants, diminishing their capacity to improve water quality and provide other services. For example, in Egypt the seasonal flooding of riparian wetlands has sustained the population for millennia, but recent water-related infrastructure projects have threatened this natural dynamic. Similarly, the inundation of riparian wetlands in South America's Amazon River basin has provided spawning habitat for fishes upon which local populations depend for protein. Inundation of these areas for hydropower production, deposition of silt from mining and agricultural activities, and human migration patterns that modify demands for water, transportation, and energy all threaten the integrity and sustainability of these critical systems.[2]

Biodiversity

The *Convention on Biological Diversity*[3] defines biological diversity as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems." Freshwater ecosystems boast a disproportionate share of the world's biodiversity. Although they comprise less than 1 percent of the planet's surface, some 12 percent of described species live in freshwater and more than 25 percent of the world's described vertebrate species depend on freshwater ecosystems at some point in their lifecycle. The International Union for the Conservation of Nature (IUCN) notes that some 126,000 described species depend on freshwater ecosystems, though the total number of species may rise to more than one million. This freshwater biodiversity offers and supports a host of ecosystem services, as described in the following section.

Freshwater ecosystems also suffer from a disproportionate loss of and threats to biodiversity, partly due to the water quality degradations described above. In the last three decades of the twentieth century, populations of freshwater species fell 50 percent on average, a rate two-thirds greater than the rate of terrestrial and marine species. In recent years, the biodiversity of freshwater ecosystems has been degraded more than any other ecosystem, including tropical rainforests (MA 2005a). The most endangered mammal on Earth is the Yangtze dolphin, while the Ganges dolphin is also endangered; additionally, the entire crocodilian

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2 Personal communication from Jeffrey Thornton
3 For information on the Convention, see http://www.cbd.int/

assemblage in both rivers is also threatened or endangered (Dudgeon et al. 2005).

The introduction of non-native species, especially fish, and increasing nutrient input rates pose the greatest water quality threats to native biodiversity (Carr and Neary 2008). Water quality impacts can lead to altered or degraded systems that support non-native species at the expense of native species. One study evaluated various factors contributing to the extinction of freshwater fish and found that non-native species, which may feed directly upon native fish or outcompete them for resources in altered or degraded systems, contributed to 54 percent of extinctions while other water quality impacts contributed to 26 percent of extinctions (in Revenga et al. 2000).

Data on threatened and endangered freshwater species vary by region, and are not encouraging. In the United States, for example, nearly 40 percent of freshwater fish species, more than two-thirds of freshwater mussel species, half of all crayfish species, 40 percent of stonefly species, and 40 percent of amphibians have gone or may soon go extinct.[4] In Europe, more than 40 percent of freshwater fish species are in imminent danger of extinction; in South Africa, nearly two-thirds of freshwater species are threatened or endangered (Revenga et al. 2000). Nearly half of all amphibian species have experienced population declines and nearly a third face extinction (Dudgeon et al. 2005). Since amphibians are indicator species and especially sensitive to water quality perturbations, their decline points to the widespread adverse impacts of pollution on global freshwater ecosystems (MA 2005a).

Effects of poor water quality on human health

Unsafe or inadequate water, sanitation, and hygiene cause approximately 3.1 percent of all deaths worldwide, and 3.7 percent of DALYs (disability adjusted life years) worldwide (WHO 2002). Worldwide, unsafe or inadequate water, sanitation, and hygiene cause approximately 1.7 million deaths a year (WHO 2002). While the majority of the health threats posed by poor water quality is the result of microbial contaminants and subsequent disease in developing countries, the historical and current use of chemicals for industrial and agricultural purposes along with the chemical byproducts of waste management are also compromising water quality, leading to other, serious health problems for wildlife and humans around the world. This section addresses the impacts of poor water quality on human health, focusing on water-related diseases and other direct human health impacts.

Water-related diseases

Worldwide, waterborne diseases are among the leading killers of children under five years old and more people die from unsafe water annually than from all forms of violence, including war (WHO 2002). There are four main classes of water-related disease: waterborne (fecal-oral), water-washed, water-based, and water-related insect vector. Many water-related diseases are the result of poor quality water that is used for drinking, washing, and other uses. Further details on two classes of water-related disease that are directly related to poor water quality are described below.

Waterborne diseases

Waterborne diseases include those for which water is the agent of transmission, particularly those pathogens transmitted from excreta to water to humans. These include most of the enteric and diarrheal diseases caused by bacteria, parasites and viruses, such as cholera, *Giardia*, typhoid, and rotaviruses. Drinking water contaminated by human or animal excreta is the main cause of water-related diseases. The first such diseases identified were typhoid and cholera, and both remain a serious problem in many regions of the world.

The most common causes of severe diarrheal disease include Rotavirus, Pathogenic *E. coli*, *Campylobacter jejuni*, and protozoan parasites. The leading cause of severe diarrhea in children is Rotavirus, and almost every child who reaches the age of five will have an episode of rotavirus gastroenteritis (UNICEF 2008). Epidemic diarrheal diseases are caused by *Shigella* and *Vibrio* cholera. Both are highly infectious and are prone to severe epidemics.

Every year, around 1.8 million people die from diarrheal diseases, 88 percent of which are attributed to unsafe water supply or inadequate sanitation and hygiene (WHO 2004b). In Southeast Asia and Africa, diarrhea is responsible for as much as 8.5 percent and 7.7 percent of all deaths, respectively. Severe and repeated cases of diarrhea contribute extensively to childhood malnutrition. Malnutrition, often caused by diarrhea that is in turn the result of unsafe water, causes 35 percent of all deaths worldwide of children 5 or younger. Fifty percent of this malnutrition is associated with diarrhea or intestinal nematode infections from unsafe water (Prüss-Üstün et al. 2008).

Over the last 50 years, deaths from diarrhea have decreased from 4.2 million deaths per year from 1955-1979 to 2.5 million deaths per year from 1992-2000 (UNICEF 2008).

4 See http://www.epa.gov/bioindicators/aquatic/freshwater.html

But diarrheal morbidity appears to be increasing: every year children in developing countries suffer from 4-5 debilitating episodes of diarrhea (UN 2006). Recurring bouts of diarrhea exacerbate malnutrition and can result in long-term debilitating effects, such as stunting and wasting. Recently studies have also made the link between chronic diarrheal disease and long-term cognitive impairment. Studies found lasting impacts in terms of reduced ability to perform on standardized tests years after the diarrheal episodes (UNICEF 2008).

There are also non-diarrheal waterborne diseases including Typhoid fever, which causes 600,000 deaths per year. Two forms of Hepatitis, Hepatitis A and E, are waterborne diseases caused by ingestion of fecally contaminated water.

Water-based diseases

Water-based diseases come from hosts that either live in water or require water for part of their life cycle. These diseases are passed to humans when they are ingested or come into contact with skin. The two most widespread examples in this category are schistosomiasis, which results from contact with snails that serve as hosts, and dracunculiasis (Guinea worm), which results from ingesting contaminated host zooplankton. There are about 160 million people in 74 countries who are infected with schistosomiasis, a tenth of whom suffer severe effects (UNICEF 2008), and schistosomiasis could be responsible for 200,000 deaths in sub-Saharan Africa alone (Zhang 2007). The disease continues to spread where irrigation projects produce habitat that favors the host snails. Major outbreaks of schistosomiasis often follow the construction of large dams. In the Sudan, the construction of Sennâr dam led to the infection of nearly the entire nearby population.

Health effects of high concentrations of nutrients

High concentrations of nutrients can pose serious risks to human health. The potential health effects of nitrates are numerous and include *methemoglobinemia* (infant blue baby syndrome); cancers; thyroid disruptions; and birth defects. Blue-baby syndrome occurs when the oxygen-carrying capacity of hemoglobin is blocked by nitrites (caused by the conversion of nitrates in the stomach), leading to oxygen deprivation and suffocation. Infants are especially susceptible because their stomachs easily convert nitrates to nitrites (see Harte et al. 1991). High levels of nutrients like nitrates have also been linked to stomach cancer and negative reproductive outcomes (Carr and Neary 2008). Nitrites react with both natural and synthetic organic compounds to produce N-Nitroso compounds in the human stomach.[5] Many of these compounds are carcinogenic in humans (IARC 1978, US NAS 1977), and a substantial body of literature suggests that high nitrate levels in drinking water may increase cancer risks (Mirvish 1983, Mirvish 1991). To date, most water agencies have not adequately addressed the contribution of nitrate in drinking water to the human cancer risk from N-Nitroso compounds.

Epidemiological evidence also points to a risk to thyroid function from drinking high concentrations of water with nitrates. One study shows an increase in hypertrophy, a condition marked by enlargement of the thyroid, the gland responsible for many of the body's endocrine and hormonal functions (Van Maanen et al. 1994). Other studies have indicated a possible link between exposure to nitrites, nitrates, and N-Nitroso compounds to birth defects. The effects of exposure were first observed in animal studies, but have since been observed in human epidemiological studies (Dorsch et al. 1984; Knox 1972; Super et al. 1981; Ward et al. 2005).

Other health impacts of water quality contaminants

A range of other contaminants are known to have direct and indirect impacts on human health, including non-organic and organic contaminants. Metals, such as mercury, copper, and zinc are naturally found in the environment; at low concentrations they are essential for ecosystem and human health. However, extended exposure or exposure at high levels can have serious consequences for humans as these metals tend to bioaccumulate in tissues (UNEP GEMS 2007). Human activities, particularly the increase in mining and industrial processes since the 19th century, have increased the concentration of metals in the environment (Carr and Neary 2008). For example, mercury, which is largely a byproduct of fuel combustion, mining, and waste-incineration (Pacyna et al. 2006), is highly toxic. Since fish bioaccumulate metals, they can contain high concentrations of mercury and expose people to concentrations sometimes tens of thousands of times higher than that found in the water source, posing a serious threat to human health (WHO 2005). The mercury found in fish and shellfish is most often methyl mercury, which is particularly toxic. Consumption of methyl mercury, particularly by small children and pregnant women, can lead to developmental and neurological damage. In adults, it has been linked to coronary heart

[5] Nitrosamines are produced from nitrites and secondary amines. Their formation can occur under certain conditions, including strongly acidic conditions such as that of the human stomach. Many of these compounds have been found to be carcinogenic in laboratory animals.

disease (Mozaffarian and Rimm 2006). Inorganic mercury also poses a range of acute and chronic health effects, with long-term oral exposure to low amounts potentially leading to renal damage and immunological effects (WHO 2003b).

Arsenic is a semi-metallic element that is highly toxic and carcinogenic (IARC 2004). Naturally occurring in subsurface formations, arsenic can readily leach into groundwater. Naturally occurring minerals are, of course, only a human health concern when humans rely on those sources for drinking, cooking, or bathing. But millions of individuals are exposed to drinking water contaminated with inorganic arsenic (Smedley and Kinniburgh 2002). Exposure to arsenic through drinking or bathing in contaminated water can lead to the development of skin lesions and cancers (Carr and Neary 2008). While evidence suggests arsenic levels in groundwater aquifers in many parts of the world are acceptably below WHO drinking water guidelines, it remains a serious health threat in some areas, including Bangladesh, India, and to a lesser extent Cambodia and Vietnam (Charlet and Polya 2006) (see the case study below). Arsenic-contaminated groundwater has also been found in Argentina, Chile, China, Mexico, Thailand, and the United States (WHO 2004b). As of 2004, 28-35 million Bangladeshis consume water with elevated arsenic levels; the subsequent number of cases of skin lesions related to drinking water in Bangladesh is about 1.5 million (WHO 2004b).

Other metals present in drinking water also pose serious health risks. Lead exposure can cause brain damage, nervous damage, blood disorders, kidney damage, and developmental damage to the fetus. Acute exposure can cause vomiting or death. While natural waters contain almost no lead, it can be leached into water supplies from distribution systems and pipes. Copper, while an essential mineral, can cause stomach irritation, nausea, vomiting, and diarrhea in relatively high concentrations (ATSDR 2004). Cadmium is also of concern as long-term, low-level ingestion is associated with kidney damage and can cause bones to become fragile and break easily (ATSDR 2008).

A wide range of persistent organic pollutants (POPs) can bioaccumulate through the food chain, with serious health and environmental impacts. These impacts often include disruption of developmental function, making small children and the developing fetuses of pregnant woman particularly vulnerable. Recognizing the threat of POPs, the Stockholm Convention on Persistent Organic Pollutants has identified an initial 12 POPs – the "dirty dozen" – that pose extreme danger to environmental and human health (see case study on the Stockholm Convention in Section III: Governance and Regulation). Exposure to POPs, either acute or chronic, can lead to a wide range of adverse health effects in both animals and humans, including endocrine disruption, reproductive and immune system problems, cancer, and death (Ritter et al. 1996).

Nine of the twelve POPs identified by the Stockholm Convention to be permanently phased out of use are pesticides. In humans, DDE accumulates in fatty tissue and has been linked to endocrine disruption and reproductive problems (Jaga and Dharmani 2003), and has been classified as possibly carcinogenic by the International Agency for Research on Cancer (ATSDR 2002).

Three other POPs of serious human health concern are dioxins, furans, and polychlorinated biphenyls (PCBs), unwanted byproducts of industrial processes and incineration. Dioxins and furans are found throughout the world in practically all media (UNEP 1999). Dioxins are very stable chemicals, and with a half life estimated to be seven-to-eleven years, they bioaccumulate in fat tissue and breast milk and endure in the body for a long time. Due to the ubiquity and stability of dioxins, all people have background exposure and a certain level of dioxins in their body (UNEP 1999). Long-term exposure to dioxins and furans is linked to damage to the immune system, developing nervous system, endocrine system, and reproductive functions; chronic exposure has resulted in several types of cancer (UNEP 1999). PCB has been classified as a probable human carcinogen (UNEP POPs). It is also linked to health problems such as low birth weight, thyroid disease, and learning, memory, and immune system disorders. PCBs in the river sediment also affect fish and wildlife (US EPA 2009).

Effects of poor water quality on water quantity

Poor water quality has an impact on the quantity of water in a number of ways. Polluted water that cannot be used for drinking, bathing, industry, or agriculture effectively reduces the amount of water available in a given area, directly impacting water quantity. The more polluted water is, the more difficult it is to treat it to useable standards. Generally, treatment processes for polluted water remove pollutants through creation of a waste sludge. The poorer the water quality of the source water, the greater the level of treatment that will be required to bring it to a useable standard, and the less clean the water that will result from treatment. Also, more polluted water requires a significant amount of energy to treat – energy use in turn has implications for water use and availability. There are also numerous characteristics of the built environment that affect water quantity and water quality. For example, impervious surfaces reduce the quantity of water that infiltrates to groundwater, affect the base flow of streams, and also increase the volume of water that runs off the land surface, creating more erratic stream flows and conveying greater amounts of contaminants. Both reduce the quality of water. At the same time, actions that improve water quality

Case study

Arsenic in groundwater

The case of arsenic in groundwater in southern Asia has become a classic example of the risks of groundwater contamination, the human health consequences of failing to monitor groundwater quality, and the failure of governmental organizations at all levels to protect the public from water quality problems. Arsenic is a metalloid element known for its toxicity. It is relatively soluble in water and occurs naturally in the environment in both organic and inorganic forms. Humans can be exposed to arsenic through many pathways, including air, food, and water.

Between the early 1970s and the present time, millions of groundwater wells were drilled in Bangladesh, West Bengal India, and Nepal to provide communities with a source of water other than that traditionally used – unreliable water from ponds and shallow hand-pumped wells vulnerable to drought, floods, and contamination with untreated human and animal wastes. These wells led to a great improvement in local health, improvements in food-grain self-sufficiency, and a reduction in traditional water-related diseases associated with drinking water with bacterial contamination, especially cholera and diarrheal diseases. It is estimated that 95 percent or more of Bangladeshis now use groundwater for drinking.

The possibility that this groundwater could be contaminated was overlooked. In a public-health crisis of potentially catastrophic proportions, elevated concentrations of arsenic have now been found in the groundwater of Bangladesh and neighboring West Bengal, India (Gleick 2001). Millions of people live in areas where drinking water is now known to have arsenic concentrations above – often far above – acceptable levels and thousands of people have been diagnosed with symptoms of arsenic toxicity. According to researchers, about 1/3 of the tube wells in Bangladesh produce water exceeding the arsenic standard of 50 ppb (parts per billion). In some areas, arsenic levels are as high as 2000 ppb, 40 times over the acceptable level for drinking, and most of the contaminated wells have levels of 200 to 400 ppb of arsenic (MIT 2002).

The discovery of elevated levels of arsenic in groundwater in the early 1980s led to a major research effort to understand the scope and severity of the problem, and a wide range of governmental and non-governmental efforts to develop technological, educational, and social solutions. Galvanized by growing concerns among local communities, scientists, the public, and health professionals, a serious effort at evaluating the nature and scope of the problem began in the mid-1990s, with an increasing number of studies carried out by governments, university scientists, non-governmental organizations, and international agencies. Of great concern to health specialists is that symptoms of chronic arsenic poisoning may take between five and fifteen years – or even longer in the case of cancers – to reveal themselves. The period depends on the amount of arsenic ingested, the length of exposure, and susceptibility of the person. It is thus possible that the vast numbers of tube wells installed in Bangladesh in the last three decades have been slowly poisoning their users since they began operation. It is also possible that many of the worst health impacts may not appear for a number of years.

Various responses to the problem have been taken or suggested. National governments in Bangladesh, India, and Nepal have formed partnerships to address the situation through data collection, public health programmes, water purification efforts, and efforts to find alternative sources of safe water. UN agencies such as UNICEF have funded research on the extent of the arsenic problem and are assisting in developing technologies for water purification such as inexpensive filters and finding alternate sources of safe water, such as rainwater harvesting. With government ministries and NGOs, UNICEF launched a programme to train doctors and health workers to be able to diagnose arsenic patients and give them proper advice. The World Health Organization has supported studies on arsenic contamination and its effects on human health and has provided specific epidemiological expertise.

Because individuals cannot remove arsenic from water by boiling or the use of normal filters, the most important action is to provide arsenic-free drinking water. This water is available, but only if the arsenic concentrations in wells are actually monitored and if people can be prevented from using wells with high concentrations of arsenic. Rapid detection of arsenic-contaminated tube wells, proper watershed management, community participation in decision making, provision of safe water, treatment of ill people, and health education are all essential responses (Das et al. 2009).

can also increase the quantity of water that watersheds produce. Forested areas help to filter water and enhance water quality prior to runoff entering into waterways.

Effects of poor water quality on vulnerable communities

Vulnerable communities are disproportionately affected by poor water quality. These communities include those that live near waterways of compromised quality, are forced to travel long distances to reach safe water supplies, and suffer the most from diseases caused by unsafe water. Poor water quality has the greatest impact on marginalized communities and those that lack political and economic power. Groups that are most affected by poor water quality include the poor in developed and developing countries, women, and children.

Women

Women are the primary managers of water in most developing countries. Throughout the developing world, women and children have to travel long distances to procure water for domestic consumption. The UN Development Report estimates that 40 billion mostly woman-hours per year are spent collecting water in sub-Saharan Africa alone (UNDP 2006). Similar rates are found in South Asia, with NGOs in rural areas reporting that women walk 2 km or more to their daily drinking water source (Ray 2007). Women also report travelling further to collect water of suitable quality, because when water quality in nearby water sources declines, women and children are forced to travel further to access water. This adds to the overall “time poverty” that women experience as a result of lack of access to safe water. Because women and children supply most water for the household, polluted water affects them the most because of the increased contact they have with unsafe water (Cap-Net/GWA 2006).

Unequal power relations place women in a disadvantaged position. Of the poorest people in the world, a shocking 70 percent are women. Women worldwide experience lower incomes on average and are more susceptible to unemployment (Cap-Net/GWA 2006). Where decline in water quality impacts the availability of water, more powerful groups have the advantage when accessing limited safe water sources. In West and South Darfur, of the nearly 500 women treated for rape, a majority – 82 percent – were attacked while conducting daily activities such as gathering water (MSF 2005, Human Rights Watch 2005).

Women also bear the primary responsibility of caring for sick children and family members who fall ill due to unsafe water. Some researchers estimate that this time poverty may even far outweigh the amount of time women spend to collect safe water.

The lack of safe sanitation not only affects water quality but also severely compromises the safety and security of women. In developing countries, 1.3 billion women and girls live without access to a private, sanitary toilet. The lack of such a necessity forces women to go to the toilet in the open and under the cover of night, often risking rape and violence in the process (WHO and UNICEF 2004). The lack of safe sanitation at school also dissuades girls from attending school after menstruation, further limiting educational equality for girls.

Unequal power relations within families and in communities directly affect the health of women and girls. Women and girls are often forced to forgo necessities for the health of men and boys. Some studies have found that in times of shortages, the health of women and girls diminishes before that of males. The United Nations Human Development report found that in India reduced rainfall is more strongly associated with deaths among girls than boys (UNDP 2007).

Children

Children are by far the most affected by the lack of clean water, and have the least power to affect improvements in water quality. The overwhelming majority of deaths from water-related diseases, over 90 percent, are the deaths of children under the age of five. Every year 1.5 million children die as a result of unsafe water (UNICEF 2006). Worldwide, more than 125 million children under the age of 5 live in households without access to improved drinking water, and 280 million children under five live in households without safe sanitation (UNICEF 2006). Unsafe water and lack of sanitation and hygiene make up 18 percent of under-age-five deaths, and is one of the leading causes of mortality among children in developing countries.

The future opportunities of children are also limited due to the lack of safe water and sanitation. Children, particularly girls, who spend hours each day seeking sources of clean water for the household, do not have time left for education. The lack of toilets in schools prevents girls from attending, and water-related diseases affect the ability of children to attend and succeed in school. In addition to falling ill from diarrhea, the lack of clean water leads to intestinal worm diseases primarily affecting children of school age, impairing cognitive functions and reducing physical growth and fitness (UNICEF 2006). Every year, 133 million cases of hookworm, roundworm, and whipworm are discovered. Many more are often undiagnosed and untreated. These worms have a significant impact on development in childhood. Children in poor environments often carry 1,000 parasitic worms in their bodies at any time. A typical roundworm infection consumes one-third of the food a child eats. This further leads to malnutrition, which is implicated in 50 percent of childhood illnesses (UN-Water 2008a). Every year, 443 million school days are lost due to water-related illnesses (UNDP 2006).

Economically disadvantaged

The very poor in urban area often live along the banks of waterways, because this land is often in public ownership. Lacking other options, the dwellers in these informal settlements use the waterways to directly discharge sewage, sullage, and solid waste. Slum dwellers and those without adequate access to safe and affordable water often use these same polluted water systems for washing, bathing, or drinking, and are thus at high risk for water-borne disease.

While the overall percentages and numbers of people with access to safe water and sanitation in each of the global regions tell an important story, there are also some important disparities that exist within countries and among countries. A UNICEF/WHO study in developing countries found that the richest 20 percent were four times more likely to have access to sanitation than the poorest 20 percent. And while fewer than 4-in-10 of the poorest households had access to improved water, 9-in-10 of the richest households had access (WHO and UNICEF 2004).

Where water resources are scarce, there is competition for the little available potable water, and those at the lowest end of the power spectrum, poor women and men, will go without. A third of people without access to safe water live on less than a dollar a day, and more than two thirds of those without an improved water source live on less than US$ 2 a day (UNDP 2006). The urban/rural gap in sanitation access has narrowed in the last 15 years, although the divide between urban and rural access in sanitation is significantly larger than it is in drinking water. In developing countries, access to sanitation in rural areas nearly doubled, from a very low 17 percent to 33 percent, between 1990 and 2004. During this same period, access to sanitation increased from 68 percent to 73 percent in urban areas. Thus, people in urban areas are still more than twice as likely to have access to a toilet as those in rural areas. Two billion people of the 2.6 billion without access to sanitation live in rural areas. South Asia and East Asia have low rates of access to sanitation in rural areas (28 percent), while over 60 percent of the urban population has access. Western Asia reports nearly universal coverage in urban areas (96 percent), while only 60 percent of those in rural areas have access to sanitation (UNICEF 2006).

Poor water quality feeds the cycle of poverty. Those who have the least access to water and sanitation are also often the least likely to have health care and stable jobs. Bouts of waterborne disease reduce income further, and for the most vulnerable, often lead to death.

Effects of poor water quality on livelihoods

Clean water and healthy freshwater ecosystems provide the basic goods and services upon which many livelihoods depend, including irrigation water, fertile floodplains for agriculture and grazing, and habitat for fish and shrimp that may be eaten or sold. The need for adequate *quality* of water to support livelihoods has been emphasized less than the need for adequate *quantity* of water. In reality, both are necessary and polluted water can reduce or eliminate the viability of many livelihoods.

A study of economic effects of water pollution in an Indian village found that agriculture was affected severely by water contamination. This study compared two villages in Andra Pradesh, one which was polluted by nearby industries, and the other which was not. In the polluted village, water contained very high levels of arsenic and had abnormally high chemical oxygen demand, total dissolved solids, and other contaminant levels. The amount of land under cultivation in this village declined by 88 percent over nine years after being affected by water pollution. The loss of cultivable land is attributed solely to contamination of soils from polluted irrigation water (Reddy and Behera 2006). In addition to the destruction of productive land, water pollution caused corrosive damage to agricultural equipment and well water pumps. This study also found significant impacts on livestock. All of the local water bodies in the village were polluted, and due to inadequate municipal water supplies, livestock were forced to depend on polluted drinking water. Drinking this water sickened livestock, resulting in 149 animal deaths over 5 years. In the non-polluted village, no livestock mortality or morbidity was reported as a result of water pollution. The polluted water also resulted in lost reproductive capacity of some livestock and production of poorer quality milk and manure.

Water pollution can cause a decrease in fish production either by reducing or eliminating fish populations or by making fish unsafe or undesirable for consumption. For example, in Lake Manzala in the north-eastern Nile Delta in Egypt, fish began to have a high incidence of organ malformation and discoloration due to pollution. While fish from Lake Manzala had once provided 30 percent of all fish consumed in Egypt, people became wary of eating the fish because of the effects of pollution, and fishing in the lake has decreased (GEF 2006). A 2000 assessment by the World Resources Institute concluded that water pollution was a major threat to inland fisheries in nearly all regions of the world (Revenga et al. 2000).

Some studies have quantified the economic impacts of poor water quality on livelihoods. For example, one study quantified the effects on local livelihoods of water pollution from a large-scale mining spill in the Philippines, using surveys before and after the spill to quantify impacts. The spill, which released 1.6 million cubic meters of mine tailings into the Boac River, had widespread impacts, affecting around two-thirds of households interviewed. Livelihoods affected included coastal and river fishing, crop farming, and farm trading. Estimated forgone income in the ten years following the spill was estimated at around US $7 million (in 1996 dollars) – which was more than twice the amount offered in compensation from the mining company (Bennagen 1997).

Economic costs of poor water quality

Poor water quality has many economic costs associated with it, including degradation of ecosystem services; health-related costs; impacts on economic activities such as agriculture, industrial production, and tourism; increased water treatment costs; and reduced property values. In some regions, these costs can be significant. For example, the estimated costs of poor-quality water in countries in the Middle East and North Africa range between 0.5 and 2.5 percent of GDP per year (see Figure 5 below) (WB 2007). Additionally, poor countries with access to clean water and sanitation services experienced faster economic growth than those without: one study found the annual economic growth rate of 3.7 percent among poor countries with better access to improved water and sanitation services, while similarly poor countries without access to improved water and sanitation had annual growth of just 0.1 percent (Sachs 2001).

Ecosystem services

Ecosystems provide humanity with a broad range of fundamental market and non-market benefits. These benefits, known as ecosystem services, include provisioning services such as food, water, and fiber; regulating services such as wastewater treatment; cultural services that include recreation and aesthetic and spiritual benefits; and supporting services such as photosynthesis and nutrient cycling (MA 2005b). One influential study estimated the global value of ecosystem services at roughly double the gross national product of the global economy (Costanza et al. 1997).

The Millennium Ecosystem Assessment (2005a) found that the total economic value of unconverted wetlands was often greater than that of converted wetlands. The greatest single service freshwater ecosystems provide – marshes in particular – is water purification and the assimilation of wastes, valued at US$ 400 billion (2008$) worldwide (Costanza et al. 1997). For example, Uganda's Nakivubo swamp bestows an estimated US$ 363 million worth of wastewater treatment services annually to the citizens of Kampala (UN WWAP 2009).

People have long relied on these natural processes to clean water, dumping agricultural, municipal, and industrial wastes into freshwater ecosystems for hundreds and thousands of years. Often, however, the magnitude and toxicity of these wastes overwhelms the capacity and resilience of such ecosystems, degrading water quality locally and regionally. These degradations manifest themselves in impaired amenity values, declining biodiversity, and diminished ability to provide wastewater treatment and other ecosystem services (Carpenter et al. 1998).

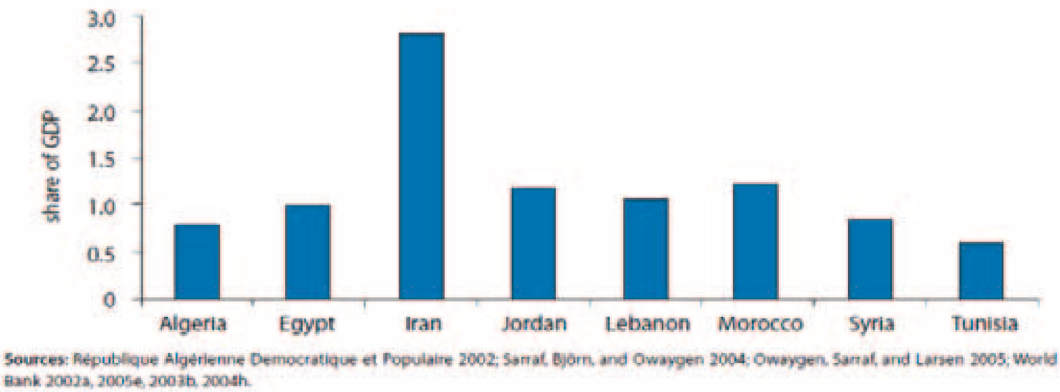

Figure 5. Annual Cost of Environmental Degradation of Water. *Source and copyright holder: Bank for Reconstruction and Development, The World Bank.*

Eutrophication – resulting from excessive inputs of nitrogen and phosphorus – diminishes various provisioning, regulating, cultural, and supporting ecosystem services. Eutrophic waters are more expensive to treat to drinking water standard; produce fewer fish; suffer decreased amenity and recreational values (see Lake Atitlán case study above); and pass greater nutrient loads downstream. In the 1990s, freshwater eutrophication in England and Wales imposed damage and remediation costs of some US$ 200 million annually (MA 2005b).

Human health-related costs

Economic benefits of improved health as a result of better water quality can be measured in a number of different ways, but typically take into account parameters including productivity loss, treatment costs, and the value of prevented deaths. Increased health has economic benefits to governments through reducing needed expenditures on disease treatment; benefits to individuals through reduced expenditure on disease treatment, transportation to seek treatment, and lost time in seeking treatment; and benefits to the agricultural and industrial sectors through improved productivity and fewer expenses associated with employee health care (SIWI 2005).

Human health-related costs can be very significant – for example, economic losses as a result of the mortality and morbidity impacts from the lack of water and sanitation in Africa are estimated at US$ 28.4 billion or about 5 percent of GDP (UN WWAP 2009). As water quality degradation continues, the prevalence and impacts of disease will increase, particularly among the poor and vulnerable (MA 2005a). And sanitation and drinking water investments are found to have high rates of return: for every US$ 1 invested, there is a projected $3-$34 economic development return (UN WWAP 2009).

Many recent studies on health-related costs of poor water quality are in reference to the water and sanitation Millennium Development Goals (MDGs). The United Nations, its member countries, and non-governmental partners committed to a set of MDGs to address the interrelated needs of the world's poorest communities. Water and sanitation are explicitly recognized as targets in the Millennium Development Goals: the international community committed to halving the proportion of people without access to safe water and sanitation by 2015. If this goal is met, it is estimated that 322 million working days per year will be gained, the value of which is nearly US$ 750 million (SIWI 2005). Meeting the MDG on water and sanitation would also result in an annual health-sector cost saving of US$ 7 billion. Overall, the total economic benefits of meeting the MDG target have been estimated at US$ 84 billion (SIWI 2005).

Agriculture

Water pollution affects the economic productivity of agriculture by destroying crops, reducing crop quality, and/or diminishing yields. For instance, there is a long history of agricultural collapses associated with the salinization of the soil and water associated with irrigated agriculture. Throughout history, societies have collapsed due to decreased crop yields associated with increased salinity (Postel 1999) (see case study of Pakistan below). It has been estimated that land degradation of irrigated lands, particularly from salinization, has resulted in the loss of US$ 11 billion from decreased agricultural productivity worldwide each year (Revenga et al. 2000, quoting Postel 1999). In addition, as the quality of surface and groundwater is degraded, farmers often must find new sources of water, which are typically expensive and contentious, often leading to significant political and military transboundary conflict (see, for example, Cooley et al. 2009).

Industrial production

While industrial production can affect water quality, industrial production can also be negatively impacted by poor water quality. Water is critical to many industrial processes, such as heating and cooling, generating steam, and cleaning, and as a constituent part of some products, such as beverages. Most industrial uses require water of a certain quality; some have higher quality requirements than others. Water pollution can

Case study

Water and soil salinization in Pakistan

The Indus basin, which makes up much of the current-day Middle East, was once the floor of a shallow sea. When the sea receded, it left salts in the soils and groundwater. These naturally occurring salts were then augmented by the advent of large-scale irrigation in the nineteenth century, which added extra water and salts to the system. In the mid-twentieth century, almost a half-million hectares of irrigated land in Pakistan were going out of production annually due to salt build up and a rising, saline groundwater table (Postel 1999). And another nearly 5 million hectares of agricultural land were threatened with reduced productivity due to high salt concentrations.

In the 1960s, Pakistan established a Salinity Control and Agricultural Reclamation Program, which focused its efforts on drilling wells to lower the groundwater table and provide supplemental irrigation water. This came at great cost – by 1990 the nation's cumulative costs for salinity control were approximately US$ 1 billion – not including lost revenue due to reduced agricultural productivity.

Today, Pakistan confronts new problems: groundwater use (originally encouraged by the government) has reached unsustainable levels and salinity is increasing as groundwater is continuously re-applied to irrigate crops.

affect industries in several ways. Poor quality water may force an industrial facility to relocate, find a new source of water, or halt production, or it may decrease the quality of the product.

Each of these impacts has costs associated with it. No estimates exist on worldwide costs of poor water quality to industry, but some studies have been done in China. In 1992, China's industrial sector lost approximately US $1.7 billion as a result of water pollution (SIWI 2005). A study on the Tongliang County Silk-making Plant found that decreased quality of silk due to water pollution reduced the plant's production value by 3.1 percent in one year (Yongguan et al. 2001), and a study in the municipality of Chongquing estimated the cost of water shortages due to pollution to be US$ 21 million.

Tourism and recreation

Tourism has grown quickly in recent decades, and is now a major source of employment worldwide. Tourism directly or indirectly supports an estimated 8.1 percent of all jobs worldwide and accounts for 10.4 percent of total world GDP (UNEP and UN-WTO 2005, quoting the World Travel and Tourism Council). Water pollution can result in large losses in tourism revenue. In the Philippines, tourism losses due to water pollution represent around 70 percent of the total US$ 1.3 billion annual economic losses from water pollution (WB 2003). In South Africa, where ecotourism has become one of the country's largest income generators, pollution on the Olifants River has resulted in wildlife mortality, which will likely have a negative impact on the tourism economy (Oberholster 2009). In the United States, loss of recreational use of freshwaters due to eutrophication alone is estimated to cost between US$ 0.37 and 1.16 billion per year (Dodds et al. 2008).

Mining

Mining operations frequently require extensive and expensive waste treatment, and degradation of water resources can have long-term negative impacts on economic opportunities in the surrounding areas. For example, acid mine drainage in South Africa " threatens the scarce water resources of South Africa, and as a result also human health and food security in mining areas" (EAT 2008). Unfortunately, few studies exist quantifying the costs of these externalities. The aforementioned Philippines mine spill in which 1.6 million cubic meters of mine tailings were released into the Boac River was estimated to cost US$ 7 million (in 1996 dollars) in forgone income in the ten years following the spill, more than twice the amount offered in compensation from the mining company (Bennagen 1997). In 1998, a mining-related accident in Spain, in which a dam failure caused the release of approximately 5 million cubic meters of toxic sludge into the River Agrio, cost US$ 44 million in regional governments' clean-up costs, plus another US$ 53.3 million in government acquisition of land polluted by the spill (UNECE 2007). In the U.S. alone, there are an estimated 500,000 abandoned mines (Abandoned Mines Portal). Managing and remediating the pollution caused by these abandoned mines will cost more than US$ 20 billion, and many of these sites will require management in perpetuity (Septoff 2006).

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III. Water quality solutions

Solving water quality problems requires strategies to prevent, treat, and remediate water pollution. As a first-order intervention, pollution can be prevented before it enters waterways; second, wastewater can be treated before it is discharged; and third, the biological integrity of polluted watercourses can be physically restored through remediation.

Wastewater is a byproduct of human waste transport and industrial and agricultural use. We can control wastewater in three ways: 1) actions at the point of generation; 2) pretreatment of wastewater prior to discharge to municipal systems or local waterways; and 3) complete treatment and reuse.

In most industrialized nations, water quality improvement efforts focused on two approaches: the construction of centralized or on-site water-treatment facilities and wastewater plants; and regulations aimed at individual "point source" polluters who discharge water pollution, including both "direct" dischargers who discharge effluents into receiving waters and "indirect" dischargers who release pollutants into sewer systems that flow into treatment plants. Among the most difficult water-quality challenges is dealing with "non-point source" pollution. Non-point source pollution is the result of precipitation runoff from many diffuse sources including fertilizers, nutrients, and pesticides from agriculture; and oil, grease, and toxics from urban settlements. These diffuse pollutants from multiple sources are not easily regulated; efforts to address point sources have been more successful to date.

There are both technological tools and approaches for meeting water quality goals and non-physical approaches such as pricing, economic incentives, and legal/regulatory tools. There are also methods to restore water quality and watershed systems through ecohydrological approaches. Healthy, resilient ecosystems play an important role in preventing pollution before in enters waterways, in treating and restoring polluted waters. Below is a summary of the three fundamental ways to protect water quality.

Pollution prevention

Introduction and overview

Preventing pollution at its source, in industry, agriculture, and human settlements, is often the cheapest, easiest, and most effective way to protect water quality. In an industrial setting, this strategy is commonly called cleaner production, and the need for both government and industry involvement in promoting cleaner production was articulated in Agenda 21 at the United Nations Conference on Environment and Development in 1992, and again ten years later at the World Summit on Sustainable Development.

Pollution prevention is the reduction or elimination of wastes from the source. Source reduction, the first and most important pollution prevention strategy, reduces or eliminates the use of hazardous substances, pollutants, and contaminants. The elimination or reduction of contaminant use can be accomplished by:

- in industry, reformulating products that produce less pollution and require less resources during their manufacture and use;
- in agriculture, reducing the use of toxic materials for pest control, nutrient application, and water usage;

- in human settlements, reducing the amount of hazardous materials used and disposed and reducing wastewater production;
- modifying equipment or technologies so that they generate less waste;
- implementing better training, maintenance, and housekeeping so that leaks and fugitive releases are reduced; and
- reducing water consumption.

Pollution prevention is distinct from pollution control in a number of key ways. Pollution control or "end-of-pipe" practices, such as waste storage and transport; recycling (except for in-process recycling); energy recovery; waste treatment; waste disposal; and waste segregation are distinct from pollution prevention in that they treat waste after it has been created. Pollution prevention strives to reduce the overall generation of waste. An important advantage of pollution prevention over pollution control is that the former protects all environmental media (air, water, and land) simultaneously, while the latter may shift waste from one medium to another (e.g., an air pollution scrubber can send air contaminants into water).

There are also tremendous financial benefits that can be gained from a pollution prevention approach. Waste is predominantly a cost for a business or utility. Generation of waste in a process is a demonstration of inefficient use of materials and resources; pollution prevention can turn waste streams into valuable resource streams. Pollution prevention gets at the root causes of pollution, namely waste and inefficiency. Preventing pollution means less money spent on waste handling, storage, treatment, remediation, and regulatory monitoring.

Source water protection

Increasingly, water planners and communities are looking to source water protection as a key to improving water quality and decreasing treatment costs. The traditional approach to water management involves treating water at many stages to remove contaminants. The environmental and economic costs of this strategy are high, particularly as energy costs rise. A new paradigm is emerging, which focuses on protecting the sources of vital drinking water supplies from contamination in order to reduce or eliminate the need for treatment. Healthy, resilient ecosystems help purify and regulate water, thereby avoiding pollution entering into waterways.

New York City has the largest unfiltered surface water supply in the world, fed by runoff from the nearby Catskills Mountains. An essential part of New York City's water supply is source water protection. In the 1990s, upgrades to New York City's water system were necessary to continue to supply a growing population with high-quality drinking water.

The first option considered was the construction of a water filtration plant at a cost of approximately US $6 billion, with annual operating costs of $150 million. Because of the high cost of the filtration plant, the New York Department of the Environment decided to take a different approach. For far less money, the Department launched a watershed protection programme in drinking water source regions which included enactment of regulations governing activities in the watershed (especially septic system siting); innovative planning initiatives; development and funding of best management practices for farms; and land acquisition.

Industrial point-source pollution

Preventing pollution in the industrial setting is most commonly known as cleaner production. Because industrial releases are fixed sources, they are often regulated. Thus, it is easier to characterize the quality of existing effluent, and there are greater regulatory and financial incentives for industries to prevent pollution and reduce costs. Cleaner production efforts have been supported through UN programmes, including through UNEP and other organizations. In 1994, the United Nations Industrial Development Organization (UNIDO) along with UNEP established the National Cleaner Production Centres Programme (NCPCs), which helps developing countries and countries with economies in transition to incorporate cleaner production into their industrial development and environmental legislation, and undertake activities to support cleaner production.

The basic concept behind cleaner production is to increase the efficiency of use of raw materials, energy, and water and reduce sources of waste and emissions. Cleaner production can take place in a number of ways:

- reducing or eliminating use of solvents in industrial processes;
- reducing or eliminating the use of toxic chemicals in processes;
- reducing overall water use in the system; and
- closing the water cycle within industries and eliminating wastewater discharge.

Cleaner production has the dual benefits of reducing environmental impacts and increasing productivity and competitiveness (UNIDO). For example, an in-plant

Case study

Cleaner production at a tannery in Zimbabwe

In many African countries, leather-making is an important source of income, however, it can also be a major source of water pollution (UN WWAP 2003). Imponente Tanning Ltd, a tannery in Harare, Zimbabwe, had high chemical oxygen demand (COD) levels in its wastewater, caused by the use of sulfides and other chemicals used to remove the hair from hides by dissolving the hair. The city of Harare charged the company for treating its wastewater based on COD levels, which became very costly for the tannery. Through the Cleaner Production Technology (CPT), a joint project between Zimbabwe and the Danish International Aid Agency (DANIDA), the tannery implemented a new process which allowed for the hair to be removed without dissolving it. The hair is then filtered out of the wastewater and can be used as fertilizer (SIRDC).

The adoption of this process reduced COD levels in wastewater by 50 percent, resulting in significant savings to the company. Additionally, the project had a short payback period of around three years (the project cost was US$ 40,670, and annual savings were US$ 13,500) (SIRDC).

assessment carried out by Cuba's National Cleaner Production Program helped a juice company to increase juice production 23 percent and raise its annual income while, among other environmental benefits, reducing the wastewater pollution load concentration by 40 percent. The Guatemalan Cleaner Production Centre helped a dairy company reduce their wastewater generation by 99 cubic meters per month while realizing significant economic savings (UNIDO).

Agricultural non-point source pollution

As noted above, agricultural activities around the world contribute significantly (about 70 percent on average) to water-pollutant loads. Contaminated agricultural runoff often includes nitrogen, phosphorus, pesticides, and sediment, which impair both surface and groundwater. There are several ways to reduce the impacts of agriculture on water quality, and scales of intervention from the farm level to the state.

Farm level

At the farm level, many innovations have decreased the need for chemical inputs. In particular, organic, or biological, agriculture is a movement away from synthetic chemicals in favor of crop rotation, mulching, composting, cover cropping, and integrated pest management. Crop rotation has long been used to avoid depleting soil nutrients. In addition, less intensive tillage practices that leave varying amounts of crop residue or mulch on the soil have been shown to increase soil organic matter without the use of synthetic fertilizers. Cover cropping with clover, vetch, and other nitrogen-fixing plants is another practice that enhances soil health without the use of chemicals. Also, composting plant matter and animal manure produces a rich soil that can be applied to fields.

To reduce pesticide inputs, some farmers are shifting to integrated pest management techniques. Integrated pest management uses particular cultivation practices and beneficial insects to control pests. For instance, crops are watched closely and any diseased specimens are quickly removed or quarantined. Should a pest reach an unacceptable level, mechanical methods are often used, including erecting insect barriers and using traps, vacuuming, and tillage to disrupt breeding and reproduction of pests. Natural controls are then used such as beneficial insects, fungi, or bacteria that will eat or negatively affect the pests. In some cases chemicals may be used, but they are targeted to particular types of insects – rather than broad-spectrum pesticides that can affect many insect species beyond those of concern.

Finally, reducing the total amount of water that is applied to fields decreases the leaching of nitrates and other chemicals into water bodies. The use of drip irrigation is increasing throughout the world; drip and other micro-irrigation systems reduce the water lost to evaporation and deep percolation and therefore are more efficient in terms of water-use than flood or sprinkler irrigation. Many farmers also distribute fertilizers through drip systems and report that they can use far less because the fertilizer is precisely applied to the crop roots. Any remaining agricultural runoff (or drainage) should be collected in drains or tailwater recovery ponds to be reused. Since drainage water usually contains some amount of fertilizer, reapplying the water can reduce the need for additional nutrient inputs.

Basin level

At the basin level, the types and locations of different land uses should be considered to control agricultural water runoff. In particular, steep slopes facilitate the runoff of water, sediment, and chemicals from agricultural lands. Contour farming and terracing can decrease erosion and runoff from agricultural fields and are critical for pollution prevention on steep slopes.

In addition, many individual farmers receive their water from a collective water management district at a sub-basin or basin scale. These organizations can provide services to farmers that make it easier for them to convert to more efficient irrigation systems. For instance, in order to install sprinkler or drip irrigation, water must be delivered in pressurized pipes. Many water districts provide water through open canal systems and would need to upgrade parts of their infrastructure in order to provide farmers with

Case study

Programa Campesino a Campesino, Nicaragua

In 1987, the National Union of Farmers and Ranchers (UNAG) in Nicaragua founded the Programa Campesino a Campesino (PCaC), an innovative effort to promote best agricultural practices through peer-to-peer education. Today, producers from 817 communities are benefitting from the PCaC methodology where the producers share their knowledge and experiences with one another.

The practices proposed focus on local resources and conditions. In particular, the programme seeks to encourage active participation by rural communities and the transfer of know-how around organic agricultural production, sequential agro-forestry, agricultural diversification, and environmental health through implementing simple, inexpensive, and effective practices.

Practices allow for the reuse of biological matter by limiting reliance on chemical inputs and other energy-intensive technologies. Soil and water conservation are at the forefront; for example mulching and the construction of dikes, hedges, and barriers are among the methods used to conserve water, control erosion, and increase organic matter and biodiversity in the soil. In addition, rainwater collection is encouraged. In the Masaya region, they have documented a 90 percent decrease in the use of chemical fertilizers and increases in annual and perennial crop yields in conjunction with the PCaC practices of crop rotation, incorporating plant residues into the soil, using natural barriers to combat erosion, reforestation and cover crops, and spreading manure, rather than synthetic fertilizers (IFAP 2005).

Peer-to-peer sustainable agriculture education, Programa Campesino a Campesino. *Source: Union of Farmers and Ranchers* more options for irrigation. Water delivery organizations should also keep records to track water use and quality.

The Danube River Basin, which flows into the Black Sea, has suffered from poor water quality, particularly from eutrophication caused by agricultural runoff. To address this problem, UNEP and Global Environment Facility (GEF) have initiated the Danube Regional Project, one major objective of which is to reduce nutrient and pesticide pollution from agriculture by implementing best practices that reduce fertilizer application and prevent manure and other pollutants from entering waterways (UNEP-DRP).

National and state/provincial level

Finally, it is important that states set standards for agricultural practices and runoff pollutant levels and that they are able to enforce them through monitoring, measurement, and fines or other consequences for violations. In addition to enforcement, state programmes can help farmers to implement innovative practices through technical outreach and assistance. They can also provide financial incentives for adoption of farming techniques that use fewer inputs, and provide grants or loan programmes for upgrading infrastructure and installing more efficient irrigation systems. For example, in 1986, Indonesia banned the use of 57 insecticides, and subsidies for pesticides were eliminated over a two-year period (Kraemer et al. 2001). These actions were accompanied by widespread training of government field staff and farmers in biological pest management methods; by 2002, more than a million farmers had been trained (PANNA).

Settlements

Traditionally, urban and suburban development has not taken into consideration the effects on natural hydrologic processes. Settlements can reduce aquifer recharge by reducing recharge areas. The many impervious surfaces in cities – streets, roofs, parking lots, sidewalks – prohibit water from filtrating into the ground and result in large quantities of urban runoff. This runoff collects pollutants as it flows across city surfaces.

The significance of polluted runoff to water quality problems highlights the link between land use and water quality and the need to better integrate water quality concerns into development and land-use planning and policies. Smart growth strategies, particularly low impact development, have many benefits, including minimizing adverse water quality impacts of urbanization.

Smart growth is a broad land-use concept which promotes planning of development in order to protect and enhance public and environmental health and which can benefit water quality in a number of ways. For example, compact building footprints and communities help preserve natural lands which can absorb and filter stormwater. Smart growth also fosters lifestyle choices that reduce water pollution, for example encouraging walking rather than driving and small lawns which require less fertilizer and pesticides, both of which help reduce the quantity of pollutants introduced into water bodies through runoff.

Low-impact development (LID) is a category of smart growth with particular relevance to water quality. LID is a stormwater management approach that can help to minimize the negative effects of urban and suburban land use on water quality and the natural hydrology of a watershed. This is done primarily through the use of vegetation and permeable surfaces to allow infiltration of water into the ground, thereby reducing the quantity of potentially polluted runoff and allowing natural filtration through the soil to enhance water quality. A wide variety of specific strategies and practices are encompassed by the LID approach, including permeable streets and sidewalks, “green” roofs, and vegetated medians or swales that allow water to infiltrate into soils rather than flow directly into sewers (US EPA 2000). Facilities that filter stormwater through vegetation and soil have been shown to reduce total suspended solids by 90 percent, organic pollutants and oils by 90 percent, and heavy metals by more than 90 percent (US EPA 1999).

Some urbanized regions have made significant progress in designing and implementing innovative stormwater management solutions. Portland, Oregon, for example, has been a leader in implementing LID. In 2007, the Portland City Council adopted a Green Streets Resolution which promotes LID policies that reduce polluted runoff and minimize sewer overflows entering rivers and streams. These policies have a number of additional benefits, such as helping to recharge groundwater and increasing urban green space (City of Portland, Oregon, 2009). The city has also amended its code and construction practices to facilitate these policies, codifying “downspout disconnections” that reduce stormwater flows into the city’s combined sewer system by infiltrating and/or treating runoff on-site (Portland City Code Chapter 17.37) and has incorporated green street facilities into all City of Portland funded development, redevelopment, or enhancement projects as required by the City’s Stormwater Management Manual.

Urban land is constantly being redeveloped; this means that there are many opportunities for implementing LID. Additionally, LID is typically less costly than traditional stormwater management techniques, which require construction and maintenance of infrastructure, including curbs, gutters, and underground pipes (US EPA 2007). For waters which are a source of drinking water, it could also result in savings on water treatment costs. An assessment of LID systems in the U.S. and Canada found total capital cost savings of 15-to-80 percent as compared with traditional infrastructure (US EPA 2007). Still, many barriers to LID still exist, including a lack of technical knowledge regarding LID strategies and zoning and stormwater management regulations that require stormwater to be concentrated and removed from roadways as quickly as possible.

Treatment

If efforts to prevent pollution from entering water sources are ineffective or insufficient, mechanisms to treat the water to improve quality for drinking and other purposes should be undertaken. It is also necessary to treat the wastewater after it has been used for these purposes. The following sections look at drinking water treatment at multiple scales, treatment of water for other uses, and the treatment of domestic, industrial, and agricultural waste water. There are technological solutions to treat water quality to particular standards as well as ecological systems that purify and improve water quality. The range of treatment solutions from energy intensive, high-tech approaches to low-energy, low-tech approaches to treat waste water and drinking water are described below.

Drinking water treatment

Drinking water can be treated for consumption at the municipal level, the community level, or at the household level. Technologies exist for drinking water treatment at each of these scales. For the most part, developed countries provide treated drinking water that is easily accessible at a household tap. In many developing countries, limited water is available from the municipality via individual household taps. Even those residents who have access to individual household connections need to treat this water before consumption.

Municipality

Drinking water is sourced from a variety of places by utilities. It can be sourced from groundwater, rivers, lakes, canals, reservoirs, and even from seawater. After transporting water from the source, the utility needs to treat this water to ensure that it is suitable to drink by improving the physical, chemical, and biological characteristics of the water.

Water purification can involve a series of processes depending on the source water quality. Water utilities often perform screening for large debris, pre-conditioning to treat hardness and normalize pH, then flocculation to clarify the water by binding particles, settling the particles, and filtration to remove additional suspended particles and microbiological contaminants. A final phase is disinfection, which typically at a municipal scale uses chlorine or chlorine-based disinfectants which leave a residual to the tap, or ozone.

Community

Community-scale drinking water treatment systems have also been implemented. These may include community-scale filtration or disinfection plants that provide safe drinking water from existing sources. One example is the Water Health International model, where water is filtered and disinfected using ultraviolet technology. This water is then sold to residents or businesses for use in drinking and use commercial operations. In some cases, communities make a down payment to get a Water Health Center installed, and then pay ongoing service charges for the water used. Their average Center is designed to provide a community of 3,000 residents with up to 20 liters of drinking water per person per day. Water Health International is expanding the system of decentralized water purification to 600 communities in India through a US$ 15 million IFC-financed project. Other projects are underway in Mexico, the Philippines, and Sri Lanka.

Community-scale interventions for pure drinking water are also used in emergency situations and in transition scenarios. In Iraq, UNEP-IETC provided drinking water from saline marsh water through packed low-pressure reverse osmosis units that were provided to six communities in pilot projects. Other approaches were tested including PV-augmented power for water distribution at a community level and the pilot testing of solar stills (UNEP 2009).

Household

The last decade has seen an increasing focus on the importance of drinking water treatment at the household level. While, ideally, every person should have access to safe drinking water from a household tap, it has become clear that strategies to improve the quality of drinking water through household water treatment and appropriate storage could have a significant impact.

Table 4 presents the WHO-compiled estimate of the effectiveness of various interventions in reducing diarrhea morbidity. Point-of-use water treatment or treating water in the home before it is consumed through UV disinfection, chlorine, or boiling is considered an effective way of reducing diarrhea morbidity. These new analyses pinpoint the importance of improving water quality in improving health. There are numerous strategies in use to provide on-site or household water treatment, from low-cost and small-scale chlorine disinfection systems, ceramic filters, flocculation/disinfection products, solar disinfection, and household boiling to very expensive on-site systems using reverse osmosis systems, which can be either energy- or water-intensive depending on the type of system.

These “point-of-use” systems for drinking water are solving access to safe water for individual users, rather than

Table 4. Effectiveness of various WASH interventions in reducing diarrhea morbidity.*Source: WHO 2004*

Intervention	Percent reduction in diarrhea morbidity
Hygiene education	45 percent
Point of use water treatment	35–39 percent
Sanitation improvements	32 percent
Water supply improvements	6–25 percent

municipalities, regions, or villages. This approach relies on private market forces to distribute water purification options to end-users directly, eliminating community, municipal, or centralized private water development requirements. For example, the Centers for Disease Control (CDC), Population Services International, and other private and public groups developed the Safe Water System using a chlorine disinfection solution, which has been distributed in 19 countries in 5 continents. In Burkina Faso, the CDC, Ministry of Health and others partnered to conduct a nationwide social marketing, media, and distribution campaign. In the first two months, 4000 bottles of the local product were sold in the first two months, according to the CDC project website. Another system, the PuR water system provides a sachet to safely disinfect drinking water at the point of use through a mini-flocculation process.

In some regions, for example in India, drinking water is critical to provide on-site to attract potential residents in water-scarce areas without an adequate piped supply. Developers and builders in these areas in India are integrating mini-reverse osmosis (RO) facilities on-site. Developers in peri-urban areas either contract this service out to third parties, who then maintain the reverse osmosis or wastewater treatment plant, or sell this service as part of the housing package, to be managed by the homeowners association through dues.

Treatment for other uses

Agricultural use

Agricultural source water can be of much lower quality than drinking water or even industrial water, in many cases. However, in some cases water may be treated using traditional techniques such as those described for municipal drinking water, or through bioremediation. Increasingly, agricultural areas are looking to recycled human wastewater as a new, drought-proof water source. In some countries, regulations have been set to ensure that recycled water is safe for agricultural use. Water stress concerns in Jordan led the country to implement a Water Reuse Implementation Project (WRIP) from 2002-2004, which developed demonstration projects, addressed public concerns through awareness-building campaigns, and developed multi-agency water reuse units. In addition, sustainable agriculture and forestry are increasingly seen as ways to protect source waters since they both are extensive, pervious land uses that allow groundwater recharge and are less disruptive to natural hydrology than urban areas. However, it is critical that chemical inputs are minimized in order to avoid ground- and surface-water contamination.

Industrial use

In many cases, industries require a particular level of water quality for input into production processes. Water purification may be needed to meet the source requirements for producing medicine, computer parts, high-grade chemical products, processed foods, or other industrial products. Water purification methods that are used by industry include the biological, physical, and chemical processes outlined in the municipal drinking water treatment section. Industries may need a particular level of alkalinity or distilled water, and so these particular treatment processes may need to be applied to surface, ground, or municipally supplied water to meet the water quality needs for particular processes. In some areas of the world where drinking quality water is in short supply, industries may use treated wastewater from municipal wastewater utilities, which is often of much higher quality than any existing or available surface or groundwater sources.

Wastewater treatment

Wastewater treatment can be conducted though centralized municipal-level systems (i.e., large systems that treat wastewater from many users at one site) or decentralized systems (i.e., those that treat individual homes or businesses or small groups of individual users). Centralized systems usually discharge to surface waters, whereas decentralized systems can produce water for local reuse, release to the soil or local surface water, or further treatment as needed. Traditionally, urban wastewater treatment in industrialized nations has been conducted at centralized facilities. Industrial wastewater is typically treated on-site, though a limited amount is sent to centralized, municipal systems. In many parts of the world, particularly “developing” nations, centralized systems are insufficient, unreliable, or simply absent and the wastewater of many local communities is simply discharged directly into waterways. Over 80 percent of the sewage in developing countries is discharged untreated in receiving water bodies (UN WWAP 2009). The amount of fecal coliform in Asia's rivers is 50 times the WHO guidelines (UNEP 2000).

There is an increasing trend toward decentralized wastewater treatment. Decentralized systems often provide a cheaper alternative to centralized systems, however, they are more prone to being poorly designed, have less oversight, and can be a major source of groundwater contamination if they do not adequately treat wastewater.

Domestic wastewater treatment

Municipal

Municipal wastewater consists of liquid carried by human wastes from toilets, washing facilities, kitchens, and other typical household water uses. It also includes commercial wastewater and some from industries. Wastewater quality is compromised physically (e.g., color, odor, temperature, etc.); chemically (e.g., biochemical oxygen demand, total organic carbon, etc.); and biologically (e.g., microbiological contaminants like coliforms, pathogens, viruses). To treat these water quality parameters, physical, chemical, and biological processes are used which result in two output streams, one of treated effluent, and the second of solid waste or sludge.

Physical water treatment technologies rely on separating or filtering contaminants from wastewater, or simply destroying those contaminants, using mechanical systems. Filtration is often achieved by running contaminated waters through fine grates or using reverse osmosis systems that separate often very small contaminants from water. The process of letting suspended solids settle at the bottom of a holding area (known as sedimentation) has long been used to allow for easier removal of contaminants. Mechanical means to stir water can be used to promote coagulation, which also makes contaminants easier to remove through subsequent filtering or settling processes. Boiling/incineration and irradiation are also considered physical methods and can disinfect (i.e., remove or neutralize certain pathogens) wastewater.

Chemical water-treatment technologies rely on introducing chemicals that break apart, neutralize, or aggregate contaminants. Chemical solutions are able to "clean" small pollutants – such as nutrients like nitrates and phosphates, as well as microorganisms – from wastewaters that are not captured using physical treatment methods. Chemical treatments often use either disinfection or coagulation/flocculation to clean wastewater. Disinfection is the treatment of effluent using chemicals to destroy pathogens. Historically, the most common disinfecting agent used in water treatment has been chlorine, however a variety of chemicals, such as aluminum and iron salts, ozone, and UV-light, can be used. Coagulation and flocculation is the process of destabilizing contaminants to allow them to bind smaller contaminants into larger aggregates to make them easier to separate physically.

Biological solutions rely on the natural processes of living organisms – such as microbes or plants – to treat wastewater. For example, trickling filters consist of a fixed bed of materials, such as rock, peat moss, or polyurethane foam covered with a film of microbial growth that cleans contaminants through absorption and adsorption. Activated sludge methods use microorganisms to convert carbon found in wastewater into carbon dioxide and water or to adjust nitrogen levels. Wastewater treatment systems are also increasingly incorporating outdoor "constructed wetlands" that use plant systems to break down contaminants before they are released to natural water bodies.

Community

In many places, sewerage and municipal-level treatment do not exist. This lack of municipal sewerage and sewage treatment can occur when there are very disperse ex-urban, peri-urban, or rural populations. Lack of density makes sewage collection, transport, and centralized wastewater treatment difficult. The lack of municipal treatment also exists in many parts of the developing world because of a lack of resources and government investment.

In the case of less dense settlements, or those that are disconnected from centralized sanitation systems, community-level systems can be effective at treating wastewater before it is disposed of in surface water. Community-level wastewater systems often use the same principles as centralized wastewater treatment – namely, physical, chemical, and biological treatment – and recreate them at a smaller scale.

On-site and closed-loop systems are a small but growing share of the water and wastewater sector. On-site systems are varied in form and function. They can be low-energy and low-cost systems for water collection, storage, disinfection, and waste treatment. Examples of these include ecosanitation approaches and traditional septic tanks. On-site systems can also be expensive and energy intensive, such as conventional mini-water plants (using, for example, reverse osmosis or ultraviolet technologies) and wastewater treatment plants (e.g. membrane bio-reactors).

At the same time, advances in technology are reducing the diseconomy of scale associated with small systems.

Membrane bioreactors may make high-quality treatment available at low cost at much smaller scale than was previously available. And micro-filtration, reverse osmosis, electrodialysis, and advanced technologies make it possible to treat small, intermittent water flows that are not easily treated with biological processes like activated sludge or membrane bioreactors.

Decentralized wastewater treatment is promoted by various development agencies. For example, one method of decentralized wastewater treatment, called Dewats, is sometimes referred to as “wet” ecosanitation. Dewats provides a series of modules to achieve tertiary treated water through sedimentation, baffled reactors, anaerobic filters, and polishing ponds, using relatively little energy. The Dewats system is growing in its application in peri-urban areas and small and medium-sized enterprises, particularly in areas that traditionally use water in latrines. Dewats is well established in India, Southeast Asia, and has recently spread to Africa.

The application of phytotechnology approaches such as artificially constructed wetlands can be used for stormwater runoff and domestic sewage treatment. These approaches can buffer the effects of large amounts of rainfall while retaining, transforming, accumulating, and/or absorbing certain toxic compounds that originate on impervious surfaces. This type of approach has been successfully used in the Akanoi River purification system designed to help improve the water quality of Lake Biwa (Japan) by treating storm and agricultural runoff, as well as in the on-site urban wastewater wetland system in Huaxin, Shangai City in China.

Numerous private companies have emerged to provide small-scale conventional treatment for water and wastewater. Emerging economies are increasingly requiring on-site treatment for wastewater instead of connection to overburdened centralized systems. New legislation in India requires all large generators of wastewater to treat all their waste on-site. This has led to an explosion of service providers developing water and wastewater treatment plants for offices, apartment complexes, and other users.

Speaking with developers and consultants in several developing-economy cities, it was found that many builders of flat complexes are integrating wastewater treatment and water treatment into their buildings because that is the only way to attract residents, particularly in water-scarce urban areas. While developing a mini-conventional wastewater treatment may seem expensive, costs are often one-fifth the cost of water purchased from tanker trucks or other sources. Treated wastewater can be used for gardening, toilet flushing, and groundwater recharge.

The trend is for more peri-urban and rural areas in developing and emerging countries, and in greenfield areas in developed countries, to opt out of conventional large-scale water and sewage treatment systems. Small-scale systems can require less energy, less maintenance (if they are modeled after Ecosan or Dewats), and be far less costly than extending pipes to a centralized system far afield. Small-scale systems often require more space, and may not be appropriate for dense, built-out urban areas.

This is reducing the pressure on centralized water-system expansion needs, but is complicating traditional regulatory mechanisms because drinking water or water for other purposes (e.g., toilet flushing or landscape irrigation) is provided by a variety of different sources, and waste is treated and disposed of in numerous places.

Household

Wastewater from human waste can often be treated on-site at a household level. This form of treatment is most appropriate for rural areas or dispersed settlements for public health reasons. Household sanitation can take the form of a dry or a wet toilet.

Septic tanks are a common method of household wastewater treatment from a pour flush toilet. A septic tank is a watertight chamber where wastewater from the household is conveyed, both black water from the toilet and grey water from washing. The two chambers are used to settle out solids and provide space for anaerobic processes to reduce solids and organic materials. Treatment in the chambers is not complete, and often accumulated sludge in a septic tank needs to be independently removed and dried.

There are numerous dry toilet systems (Morgan 2007, Mara 1984, Jah 2005). Some of these may be shallow toilets where a tree is planted and grown after short-term use (the Arborloo), or deep composting toilets where humic material is reused for horticulture. The overall concept of many of these toilets is part of the ecosanitation model. Ecosanitation, a method promoted by various development agencies including the Stockholm Environmental Institute (SEI) and Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), is based on closing the nutrient loop in sanitation and moving away from conventional waterborne sanitation. The traditional sanitation path was developed in countries rich with water resources, and is not often a good fit in countries facing water scarcity. In addition, a core tenet of ecosanitation is that human excreta contains valuable nutrients that can be used to help enhance food security when treated and handled properly.

Ecosanitation involves separation of urine and fecal matter, applying sterile urine directly onto plants, and composting the fecal matter (mostly drying) until it is safe for land application. This method is often used along with a set of

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toilet blocks, in areas with high groundwater levels, and in areas where there is no sewerage (peri-urban and rural). This approach has been implemented in India, China, Sweden, Africa, and parts of Eastern Europe. Ecosanitation facilities are growing rapidly in China and India and both countries host ecosanitation offices. In Guangxi province in China, a large-scale project funded by UNICEF, SIDA, and Red Cross and implemented by a local NGO, the Jui San Society, and local public Health Committees was implemented starting in 1997. This has grown to include 17 provinces in 2003, and resulted in 685,000 new ecosanitation toilets (GTZ 2005).

Industrial wastewater treatment

Industrial processes can generate significant amounts of wastewater. When this wastewater cannot be prevented or recycled on-site, it needs to be treated before disposal. Standards for industrial effluent quality are in place in many parts of the world, but in many places are not adequate or appropriately enforced. In some cases, if the industrial wastewater is not hazardous, it can be treated at the municipal wastewater treatment facility. In cases where the industrial effluent water quality is severely degraded or toxic, the industrial facility owner should be responsible for safely removing pollutants from the water before discharge and appropriately disposing of the hazardous sludge. Devices in use at the centralized municipal facility are useful at the industrial scale as well: for example, oil/water facility owners or operators may purchase equipment such as oil/water separators, waste evaporators, and reverse osmosis units.

Activated sludge processes, or trickling filters, may be useful to mitigate microbial contamination. Solvents, paints, pharmaceuticals, pesticides, and synthetic organic products can be difficult to treat in wastewater, and the goal should be reducing or eliminating use of these products, or other appropriate non-waterborne methods of disposal. Methods to treat synthetic organics include advanced oxidation processing, distillation, adsorption, vitrification, and incineration. Many toxic organic materials and heavy metals like cadmium, chromium, zinc, silver, thallium, arsenic, and selenium are also difficult to treat in industrial wastewater.

Agricultural wastewater treatment

In many cases agricultural wastewater, or runoff, is collected in order to be reused or disposed of; water of extremely poor quality may need to be treated before it can be reused or discharged. Normally, less intensive treatment options are chosen since water does not need to meet drinking water standards to be re-applied to a field or discharged into a waterway. Bioremediation is one form of treatment whereby plants, microorganisms, fungi, or their enzymes are used to filter and remove contaminants from polluted waters. In Nicaragua, for instance, farmers are experimenting with growing salt-tolerant crops that reduce the salinity of agricultural wastewater, which is typically difficult to remove without expensive, energy-intensive reverse osmosis processes. Treatment wetlands are another option, which is particularly useful in terms of the removal of nitrates, a common component of agricultural runoff, since wetlands create anoxic environments that encourage de-nitrification.

Ecological restoration and ecohydrology

Humanity has radically altered the planet, changing the climate, diverting a large percentage of world's available freshwater, doubling the rate of nitrogen fixation, and transforming land forms and habitat types from forests, floodplains, prairies, and deltas into agricultural lands and cities. These and other anthropogenic changes have led to widespread degradation of terrestrial, freshwater, and marine ecosystems; diminished ecosystem resilience and services; and to an extinction rate estimated to be 100-to-1,000 times greater than pre-human rates (Chapin et al. 2000). Over the past half century, recognition of these impacts has grown dramatically and there have been increasing numbers of efforts to protect and restore degraded and threatened habitats and ecosystems worldwide.

The Society for Ecological Restoration International (SER) states, "Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004). Restoration attempts to identify a set of historic conditions and their natural evolutionary development trajectory and return an ecosystem to that trajectory. Such efforts require understanding of historic conditions and comparable ecosystems, a long-term commitment of resources and, often, intensive monitoring and management. Even then, broader changes in the watershed or region can hinder or preclude restoration efforts, as can insufficient community involvement and support (SER 2004).

Freshwater restoration projects can be as straightforward as removing an upstream dam and recreating the stream channel to restore the river's former hydrograph, return sediments and nutrients to the system, restore historic water temperature ranges, and enable native species to migrate and compete in the dynamic systems to which they had adapted. Depending on the size of the stream and downstream requirements, dam removal projects can be relatively inexpensive. For example, the Brownsville Dam removal project in the Willamette Valley, United States removed a 33.5-meter-wide dam across the Calapooia River at a cost of about US$ 860,000, restoring more than 60 km of habitat for several threatened species, including spring Chinook (*Oncorhynchus tshawytscha*) and winter steelhead (*O. mykiss*).

Restoring natural processes such as natural streamflows often is not an option. In some cases, restoration efforts attempt to replicate natural freshwater ecosystem structures and functions with engineered structures, such as canals and headgates, though these typically cannot match the benefits generated by natural systems. Constructed wetlands, for example, may mimic some natural ecosystem functions and services, but rarely do they perform at the same level as healthy, natural wetlands (MA 2005a).

Nonetheless, many of the factors degrading water quality in freshwater ecosystems can be monitored and managed, improving ecosystem health. Indeed, there is growing recognition that ignoring the impacts of pollution can generate much higher long-term costs than acting in the short term (UN WWAP 2009). This growing recognition has led to successes in many areas. Pesticide bans, for example, have been implemented in many regions, with demonstrable improvements in water quality and ecosystem health (Carr and Neary 2008).

Historically, the costs of pollution were externalized. Polluters simply dumped and discharged contaminants into public waterways, passing the costs along to the environment, the general public, and future generations. Many efforts to address and reduce pollution attempt to force polluters to internalize these costs.

Such efforts offer several key benefits. Notably, it is often less expensive to control pollution at the source than it is to remediate it downstream or restore damaged and degraded ecosystems. Some degraded resources, such as contaminated aquifers, may simply not be feasibly restored, increasing the impetus to control or eliminate contaminants prior to release. Methods to force polluters to internalize such costs include regulations, enforcement, public pressure, and, in some cases, subsidies (UN WWAP 2009).

The key to effective restoration efforts is a clear identification of existing conditions and problems in the target resource. This initial research effort may be expensive and technically challenging, but is critical to the future success of the project. The process includes data collection and analysis, definition of existing conditions and disturbance factors, comparison with desired or reference conditions, analysis of disturbance factors, analysis of impacts of existing management practices, and then development of problem statements. These steps provide the basis for developing a desired future set of conditions, identifying scale considerations and restoration restraints and issues, and defining goals and objectives. Not until the problems and goals are well defined can restoration be implemented, followed by monitoring, evaluation, and adaptive management (FISCRWG 1998).

Even in developing countries, the costs of water quality deterioration far exceed the costs to remediate water quality. Efforts to restore the Nairobi River and Lake Victoria offer lessons for surface water restoration generally, as described in the case studies below.

Ecohydrology

There are already well established approaches which can be used to deal with pollution from point and non-point sources on a basin scale through the application of ecohydrology and phytotechnology. This approach is based on the understanding of the interrelationships between ecological processes and the water cycle in the catchment, and supports the role of ecosystem processes in water quality improvement. Linking this approach with social and economic capacities in a region by involving all water users through a watershed management council is a foundation for system solutions which incorporate environmental and social elements.

The quantity and quality of water in a given region are driven by climatic as well as biotic factors. Ecohydrology integrates knowledge from hydrology and ecology to create a more holistic approach to our understanding and management of freshwater systems:

> [Ecohydrology] considers interrelations between catchment – as a template for water and nutrient dynamics – on one side, and habitat modification and biological processes – from ecological succession, biological productivity down to nutrients circulation by the microbial loop – on the other (Wagner and Zalewski 2009).

Case study

Nairobi River Basin restoration project

The Nairobi River Basin Programme is a joint initiative between the Government of Kenya, UNEP, UN-Habitat, UNDPT, the private sector, and civil society which seeks to restore the river's ecosystem and create a healthier living environment for the people of Nairobi (UNEP-ROA). The Programme has four main objectives: demonstration of how industrial and socio-economic factors contribute to Nairobi River pollution; increase in access to information and awareness to address these factors; augmentation of capacity among stakeholders to tackle water quality challenges; and improvement of water and overall environmental quality in the basin (UNEP-ROA).

Twenty kilometers upstream of Nairobi at its origin at the Ondiri Swamp in Kikuyu, the quality of Nairobi River water is sufficient to meet drinking and irrigation needs. As the river passes through Nairobi, however, it becomes polluted by human, municipal and industrial wastes. This pollution likely contributes to outbreaks of cholera, typhoid, amoebiasis, and diarrhea, as well as eutrophication and declining biodiversity in the river (UNEP-ROA).

The Nairobi River Basin Programme investigated pollution sources, finding a host of factors contributing to the river's poor condition, including broken sanitation infrastructure and agro- and petro-chemicals, in addition to the factors listed above. The programme sought to address these problems in a way that not only reduced pollution, but educated and empowered local communities to protect water quality. A project demonstrating proper sanitation and waste disposal was initiated in a river community, constructed wetland management techniques were implemented to improve water quality, and water hyacinth purification ponds were constructed to demonstrate how to use the plant in purification of water as well as how it can be used to produce paper and household products. Subsequent evaluation concluded that community pilot projects demonstrating proper sanitation and waste management practices provided the most value, both directly through information transfer and indirectly by promoting community involvement (UNEP-ROA). The public interest generated by the programme has also lead to private sector interest and involvement in restoration and rehabilitation efforts (UNEP-ROA).

Several lessons emerged from the project. Delays in fund disbursement slowed project implementation. Project implementation began before funding was assured and sufficient planning had been completed, further delaying implementation and lowering morale. Coordination of implementing partners was not well documented, creating confusion and delays (UNEP-ROA).

Case study

Lake Victoria restoration project

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Where: Tanzania (49 percent), Uganda (45 percent), Kenya (6 percent)
Key fact: formerly enjoyed enormous biodiversity
Elevation: 1,135 m
Surface Area: 69,500 km^2
Volume: 2,750 km^3
Watershed: 184,000 km^2
Depth: Average 40 m, Max ~84 m

Prior to the 1950s, Lake Victoria featured one of the world's most diverse communities of fish, estimated at more than 500 species. At the time, some 90 percent of fish by species and 80 percent by biomass were cichlids (Haplochromis spp.). In an effort to increase commercial fish production, Nile perch (Lates niloticus) were released in the lake in the 1950s. The population of the Nile perch, a voracious predator that can grow to more than 100 kg, quickly grew at the expense of the native cichlids. More than half of the native cichlids are now extinct, or are in imminent danger of extinction. By the 1980s, Nile perch constituted some 70 percent of the fish catch. Increased sediment and nutrient loads, in addition to other pollutants, have caused algal blooms and decreased oxygen concentrations in the lake, in turn threatening the sustainability of the Nile perch fishery and potentially that of the lake's ecosystem as a whole (Revenga et al. 2000). Land-use changes, including deforestation driven in part by the need for firewood to dry the Nile perch's oily flesh, pose the greatest single threat to the basin. Heavy use of fertilizers and pesticides on farms in the basin increases contaminant loadings to the lake.

Various restoration efforts are under way in the basin, many of which seek to raise awareness of ecological conditions and best environmental practices (WLVARC 2007). The local NGO OSIENALA (Friends of Lake Victoria) owns a radio station, Radio Lake Victoria, which provides information on a variety of economic, health and environmental issues in the area. The mission of the organization is to increase local awareness about the importance of the lake, and what can be done to restore it (OSIENALA website).

The Lake Victoria Environmental Management Project, another restoration effort, is a regional development programme funded by the World Bank and GEF which is aimed at stabilizing the lake's ecosystem and making it a sustainable source of food, clean drinking water, and income, and a disease-free environment. The project is implemented jointly by the Republic of Kenya, the United Republic of Tanzania, and the Republic of Uganda (IW LEARN LVEM). Developed in 1994, the first phase of the project included monitoring efforts to help determine the primary issues affecting the lake, and pilot programmes aimed at addressing them. The second phase of the project, which is currently underway, seeks to address threats to the lake, including an initiative to support cleaner production in the basin through National Cleaner Production Centres in each country (KNCPC).

Efforts thus far have increased local awareness and capacity to address the lake's water quality and other challenges, however, it has yet to be seen if this will translate into successful restoration.

The concept was first introduced as a management approach by UNESCO's International Hydrological Programme in response to the lack of positive results in traditional flood management, water quality, and erosion control strategies (Zalewski et al. 1997). The ecohydrological approach is defined by three principles: consideration of the hydrological cycle as a starting point for assessing threats and opportunities (hydrological principle); enhancement of ecosystem robustness through understanding of the ecosystem's evolutionary established resistance and resilience (ecological principle); and creating mutual reinforcement of hydrological and ecological components of the ecosystem to strengthen its resistance and/or resilience (ecological engineering principle) (Wagner and Zalewski 2009). Application of these principles can result in reduction of water-related threats to human safety, e.g. by reducing flood risk through increasing the retention capacity and permeability of a the landscape, or by improving water quality by creating wetlands that prevent pollutants from entering waterways. In addition, an ecohydrological approach often has peripheral benefits, such as increasing recreational opportunities, improving aesthetics in urban areas, or creating new economic opportunities (UNESCO Aquatic Habitats). Examples of ecohydrological approaches exist worldwide, and three are outlined below from Poland, Iraq, and Japan.

Ecohydrological approaches have been shown to be effective in managing and restoring water quality. For example, UNESCO and UNEP have created a demonstration project intended to mitigate point and non-point source pollution on the Pilica River in Poland. The river is polluted with high nutrient loads and humic substances, leading to toxic cyanobacteria blooms in a reservoir located on the river. These cyanobacterial blooms create a health hazard because the reservoir is used for recreational purposes, and they also reduce the quality of drinking water sourced from the reservoir. A management strategy was developed after monitoring water quality threats, including studying the patterns of pollution transport into the river and studying their cause-effect relationships. Methods developed included increasing retention of pollutants in the floodplain (and thus preventing them from entering the river) through sedimentation and uptake by plants; reducing juvenile fish density, thereby reducing predatory pressure on filtering zooplankton which prevent cyanobacteria blooms; and optimizing the ecosystem's natural denitrification processes by regulating the water retention time (Wagner et al. 2009).

In Iraq, UNEP undertook a pilot restoration scheme in the marshland village of Al-Jeweber which was dewatered by 80 percent. The works included water-flow regulation, dykes, and replanting the shoreline with reeds (*Phragmites australis*). Further, a pilot project to demonstrate viable options to minimize more damage to the existing wetlands and assess the feasibility of using constructed wetlands to improve water quality on a larger scale was undertaken using the Main Outfall Drain which drains water from the city of Baghdad. While the test was not fully conclusive due to time constraints and other conditions (high salinity content) the potential of applying this approach could be considered promising

In addition, an international NGO founded in Japan in 1986, the International Lake Environment Committee Foundation (ILEC), has developed the Integrated Lake Basin Management Approach (ILBM) which considers the lake basin and its watershed as the basic unit for management. ILBM incorporates best management approaches and practices, environmentally sound technologies, and ecosystem services as part of the prevention and control of pollution into the lake ecosystem.

Groundwater

Given the cost and difficulty associated with restoration of degraded groundwater systems and the frequent time lag associated with the discharge of contaminants and their impacts on groundwater reserves, prevention is the most cost-effective and often the only feasible means to protect such systems. All forms of water, surface and subsurface, require adequate monitoring, but because the groundwater conditions cannot be readily observed, it is critical to focus resources and attention on appropriate monitoring of groundwater supply and quality (Morris et al. 2003).

As noted above, salinization of groundwater, generally from agricultural drainage, represents the single greatest threat to groundwater quality worldwide. In the lower Indus Valley, Pakistan, for example, the construction of a massive system irrigating some 14,000,000 hectares of arid lands raised the elevation and salinity of the underlying water table to such an extent that crop production declined and some lands had to be abandoned entirely. Ultimately, an extensive system of some 25,000 wells, in addition to surface and subsurface drains, attempted to extract and divert saline agricultural drainage, discharging some of these waters to the ocean. Total costs of the remediation project have exceeded US$ 1 billion to date (Morris et al. 2003).

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IV. Mechanisms to achieve solutions

The solutions to water quality problems are clear and well researched. The key question moving forward is: how can we mobilize individuals, businesses, communities, and governments to prevent pollution, treat polluted waters, and restore waterways to health? Strategies to implement water quality improvements will require awareness building, increased monitoring, and better governance and regulation. Education and awareness building efforts will build public support and political will to implement water quality improvements. Increased monitoring and data collection will help focus more attention on the problems of water quality and evaluate the effectiveness of solutions. Governance and regulation will create policies, laws, and regulations to protect and improve water quality, strengthen enforcement, and provide financing for implementation. These three mechanisms to achieve water quality improvements are detailed below.

Education and awareness building

Improving water quality, preventing point and non-point source pollution, treating wastewater before disposal, and restoring the quality of waterways all require political will. Education and awareness-building campaigns play a critical role in building community knowledge and support for the importance of protecting and improving water quality. This support for water quality improvements can lead to increased pressure on policy makers and elected officials to implement legislation and regulations to protect water quality, improve enforcement of these regulations, and increase the willingness on the part of the policymakers and elected officials to act.

In much of the developed world, the impetus for improvements in water quality arose in the nineteenth century, at the time the Public Health movement was born in England. Ongoing media attention combined with public pressure forced many of the major municipalities in the 1800s to invest in improving water quality by developing sewerage and treating wastewater. Nineteenth century London was the "cesspool city" about which the London journalist George Goodwin wrote in 1854: "The entire excrementation of the Metropolis... shall sooner or later be mingled in the stream of the river, there to be rolled backward and forward around the population."[6]

Similar conditions existed in Paris, Chicago, and almost all of the major cities in industrializing countries in the nineteenth century. Ultimately, these conditions began to have a negative impact on productivity due to illness, social and societal decay, and declines in public order. In all of these cases, increasing media attention, community pressure, and education on the impacts of poor water quality resulted in millions of dollars worth of capital investments to protect public health and water quality.

Goals of education and awareness-building efforts

Education and awareness-building efforts to improve water quality can focus on a number of areas. They can be led by community-based organizations, non-governmental organizations (NGOs), or governmental entities. Education and awareness-building efforts can change behavior among individuals, building capacity and leading to changes at community, municipal, regional, and national levels.

Key goals for education and awareness building include:

Changing individual behavior: Individual behaviors impact water quality. For example, residents living, working, or playing near waterways may dispose of solid waste, human waste, or chemicals in water bodies that impair water quality. Solid waste can clog water movement and leach toxins into

[6] Goodwin, George, as quoted in Wilson, p. 37

the water. Inappropriate disposal of human waste in or near waterways can cause serious health problems. Education and awareness-building efforts can help change behavior among individuals. An example is the numerous awareness-building campaigns in municipalities urging people to dispose of oil and grease properly to avoid letting it drain into stormwater drains, eventually compromising water quality. There are also education efforts to help people using open defecation to understand its impacts on water quality and disease. The African Youth Movement on the Environment spread awareness around the connections between health and water, helping to decrease pollution through improved pit latrines in schools and reducing dumping of refuse into streams. Due in part to efforts of the group, incidences of cholera, typhoid fever, and dysentery were cut by 75 percent in three years (Otu 2003, UNEP Fighting Water Pollution at the Grassroots Level).

Changing policy: Community education and awareness-building can help promote policies that improve water quality. Large-scale education and advocacy efforts can help inform and change national policy, which has happened in many places in the world including in India, the United States, and much of Europe. Community-scale efforts can help change local government policy that can impact disposal of municipal wastewater or development around streams and waterways. In Ukraine, for example, a group of women became concerned when they discovered that sewer overflows, caused by an inadequate sewage system, were causing sewage to flow into streets and homes. When they first approached local government, they were turned away. They then launched a political campaign and filed a legal suit, and as a result the government allocated funding to improve the sewage system, closed a hazardous oil tank cleaning facility, and funded local environmental projects (UN-Water and IANWGE). In democracies, educated citizens can approach elected officials with water quality concerns to advocate for new legislation and better regulation.

Increasing enforcement: Once adequate regulations to protect water quality are in place, enforcement is needed to achieve the benefits of these regulations. Awareness-building and education efforts can help to inform the community as well as regulators and promote increased enforcement to improve the health of waterways. Citizen monitoring often plays a critical role in alerting regulatory agencies of potential violations of water quality regulations.

Investor, consumer, or community pressure on corporations: Communities can also increase public awareness of water quality by conducting waterways assessments that identify sources of pollution into waterways. By identifying sources of water contamination originating as effluent from industries or agriculture, community organizations can put pressure on polluters to prevent pollution or treat it before it is released into waterways. A study of industrial pollution control in China, for example, found that the strength of community pressure (or "informal regulation") in changing discharge behavior was at least as strong as formal regulation (Wang 2000).

Connecting people to water quality impacts

Water quality education, awareness building, and advocacy efforts are most successful when they connect water quality to key things that people care about; it is important to connect the abstract concept of water quality to concrete issues that matter to people. Water quality needs to be made relevant to people's lives. Changing behavior, convincing policy makers, and exciting media coverage require greater attention to the numerous ways in which water quality intersects with human needs and values. There are a few key elements which can help anchor the concept of water quality in ways that relate to people's fundamental values:

Cultural or religious significance: In many cases, connecting the importance of protecting water quality to the cultural or religious significance of waterways has made a difference in increasing political will to improve conditions. For example, the Ganges River is one of the holiest rivers in India, and yet it is the dumping ground for significant amounts of human waste, solid waste, and dead animals. Recent campaigns to clean the Ganges River have appealed to the religious beliefs of Hindus and the need to keep the holy Ganges River pure.

Health: Water quality is deeply connected to health of humans, animals, and ecosystems. Appealing to the need to improve health has been an effective tool in promoting improvement in water quality. Often the connections to health have been from the drinking water standpoint. Increased education to connect health with sanitation and wastewater treatment is needed in order to improve regulations and enforcement in these areas. For example, the community-led total sanitation movement (CLTS) that originated in Bangladesh and has moved to India and Africa has been very effective at "triggering" communities to recognize the connections between sanitation, water quality, and health. This has been effective at creating a sanitation revolution in villages throughout South Asia. Frequently, water quality improvement programmes can benefit from coordination of efforts with ongoing health-related interventions, such as anti-littering campaigns and anti-malarial awareness efforts.

History: Waterways, streams, and rivers may also have historical significance. Creating awareness around the role that waterways played in the history of a particular place can be useful in improving awareness and protecting water quality. For example, in some places waterways that are polluted beyond the standards for human use today may have been favorite recreation sites of previous generations of residents. Educating residents of today with this knowledge can increase public participation in bringing back waterways and improving water quality. For example in Chennai, India, which is home to four severely polluted waterways, the older generation can still remember a time when they used to swim in the rivers. This history provides an important impetus to return water quality in the waterways to levels that existed 60 years ago.

Economy: Recognizing that water quality affects the productivity of agriculture and industry can also help increase attention to protection and restoration of quality. If agricultural producers and industrial producers can understand how poor source water quality increases their source water treatment costs or reduces their productivity, these stakeholders can also be proponents of improving water quality.

Environment: Education on the connections between water quality, habitats, and biodiversity can help increase the interest of conservationists in promoting and protecting water quality. Conservationists, anglers, birders, and others who enjoy fishing or bird watching need to understand the connections between water quality and their experiences of wildlife. Making these connections can help increase the constituency that is advocating for water quality improvements.

Documenting the problem

A first step in awareness building and education can be to document the problem. This can be done through commissioning independent studies of water quality, community-based participatory research, and/or recording the history or cultural significance of the waterways. Independent studies of water quality can uncover the characteristics comprising poor water quality and identify key pollutants and potential sources of pollution. Community-based participatory research can involve communities in asking questions about the state of waterways, designing a research study to answer the question, and implementing the study using laboratory or non-lab methods. For example, in Mexico a few NGOs and universities have designed water quality testing programmes that track water quality by identifying and categorizing aquatic life and testing for biodiversity.

Community-based volunteer monitoring programmes can supplement and extend monitoring efforts of governmental agencies as well as build a trained cadre of informed citizens who will advocate for improved water quality or water quality protection. Likewise, use of community questionnaire surveys can not only inform but also build the basis for interventions to improve or protect water quality.

Developing anecdotal non-scientific recorded histories of the importance of waterways and water health in communities can also help document the problem. Linking these oral histories to limnological parameters through questionnaire surveys or interviews can be a useful combination. These strategies of documenting the problem can then be used to educate and engage the public, activate the media, and advocate with policy makers.

Engaging the community

The community can be engaged through education and awareness-building efforts to promote better water quality behavior and also build political will for needed water quality regulations and enforcement. Involving residents in conducting community-based participatory research to document the problem is an exciting way to get residents involved in and passionate about protecting water quality, since this helps them see the impacts of pollution first hand. Engaging the community through events that connect them to the waterway can be very effective at increasing public involvement. In Varanasi, India, the Sankat Mochan Foundation hosts an event every year on World Water Day called a Human Chain, where students and residents of Varanasi link hands all along the banks of the Ganges River. The Human Chain event is meant as a shield to block pollution and solid waste from polluting the river, and to promote awareness and education of the problems of water pollution.

In many cases around the world, the actions of individuals within their own households, businesses, or communities often provide valuable demonstrations of how no-cost or low-cost actions and consumer choices can benefit the environment in general and water resources in particular. All of these actions help to enhance “quality of life” and shared community experiences.

A gender perspective needs to be deliberately integrated as a goal for water resources management, including in water quality. Research in the field of Integrated Water Resource Management has proven that the involvement of women in both analysis of project design and implementation of projects has led to improved efficiency and effectiveness in water sector programmes and a pronounced interest in environmental sustainability in water management (Ray 2007).

Recent studies, including one by the International Water and Sanitation Centre (IRC) of water and sanitation projects completed in 88 communities, found that those projects that were designed and run with the involvement of women were more sustainable and effective than those that did not have women’s participation. An earlier World Bank Study found this same link between project success and the participation of women (UN-Water 2008b).

Working with the media

A key strategy to move education and awareness efforts at larger scales is to use the media as a venue to carry messages about the importance of water quality. Public perception is informed through numerous media channels, and delivering messages through the media can be an effective way of reaching a broader regional, national, or international audience. The news focuses public attention and conversation and has the ear of policy makers and elected officials. It is important when using the media as a means to build awareness around water quality issues to provide interesting visuals, key statistics developed from research, and also provide solutions. Presenting the water quality problem without the concurrent solutions for improvements is a wasted opportunity. Fundamental to developing a media strategy is clarifying key messages and identifying what needs to change and who needs to implement these changes.

For example, the Ethiopia WASH Movement has been a successful public awareness campaign, in part because of strategic partnerships with the media. Started in 2004 under the Water Supply and Sanitation Collaborative Council, the movement targets the most vulnerable groups, choosing one slogan each year around which to increase awareness and education. Past slogans have included, "Your Health is in Your Hands," "Let Us Use Latrines for our Health and Dignity," and "Keep Water Safe" (GWP 2008). The movement has engaged media by holding forums and organizing journalist "field-trips" to increase the knowledge of media professionals (WSSCC).

Advocacy with policy makers and agencies

Public involvement, activism, and media attention can help focus the attention of policy makers and elected officials on a particular issue, and increase the pressure on them to implement solutions. Once public awareness has been raised, advocates can capitalize on the political will that has been generated to meet directly with policy makers to educate and involve them in implementing changes. The goal of many education and awareness-building campaigns is to improve public policy, regulations, and enforcement on water quality issues. Residents and affected people should come armed with research and solutions into the offices of elected officials and policy makers to demonstrate the problem and advocate for change and the needed investments to improve water quality. Educating policy makers about the problem increases their capacity to advocate with their colleagues and design policies to address identified needs. A key opportunity in educating

Case study

CLEAN India: Education and awareness building in India

Unsafe drinking water is a widespread problem India. The Community Led Environmental Action Network (CLEAN-India), a program of the Indian NGO Development Alternatives, has worked to increase awareness of drinking-water quality through monitoring and community education activities.

With a water testing kit developed by Development Alternatives, students test ground- and surface-water samples for 14 parameters (pH, Temperature, Turbidity, Fluoride, Chloride, Residual Chlorine, Hardness, Iron, Phosphate, Ammonia, Nitrate, Dissolved Oxygen, coliform bacteria, and benthic diversity) (pers. comm. Srinivasan 2009). Monitoring activities are primarily carried out by schoolchildren, from students in participating schools around 30 cities across India. These students, and others involved in monitoring activities, help raise awareness in the communities in which they are monitoring water quality.

Testing is done seasonally. If water is found to be unsafe for drinking or undesirable in another way, the community which uses the water is contacted and given recommendations on how to make the water safer. These recommendations can include pollution prevention, such as improving sanitation and hygiene around the water, treating the water to make it safe to drink, or looking for a new source of water, if there are no other viable solutions. A significant portion of waters tested are found to require purification before drinking: between 50 percent and 63 percent in 2005, depending on the season, and between 49 percent and 71 percent in 2004, depending on the season (CLEAN-India website).

This program has resulted in increased awareness of water quality issues both by the students testing the water and the communities using the water that has been tested.

policy makers is to provide them with solutions that can help protect and preserve water quality.

The global awareness programme World Water Monitoring Day aims to build public awareness and involvement in protecting water resources around the world by engaging young people to conduct basic monitoring of pH, temperature, turbidity, and dissolved oxygen in their local water bodies. The programme involves about 70 countries and 100,000 people including low-, middle-, and high-income countries, and sends free kits to schools in developing countries.

Monitoring/data collection

Measuring the physical, chemical, and biological characteristics of surface water and groundwater provides crucial information for identifying, addressing, and tackling water quality problems. By providing baseline data, trends over time, and comparisons between different water bodies, water quality data can help to: 1) determine the impacts of industrial, agricultural, and other human activities; 2) quantify the effectiveness of policies and management plans; 3) develop water-management models; 4) prioritize where management effort should be concentrated; and 5) communicate to key stakeholders about pollution, human health concerns, and degraded ecosystems.

Problems with water quality data

A key to understanding water quality challenges and solutions is collecting, storing, analyzing, and sharing water quality data. Without adequate data, serious water quality challenges are unlikely to be identified and managed adequately to protect human and ecosystem health. Conversely, by monitoring water quality and collecting and sharing water quality data, it is possible to determine if water quality in lakes, reservoirs, rivers, and groundwater is improving or deteriorating and to identify growing problems and potential solutions that require prompt action.

Despite the importance of good data, there are currently large gaps in monitoring efforts and data related to water quality, especially at the global scale. Even for data that do exist, there are numerous challenges and problems that limit its usefulness: data are often limited in scope, there are inconsistencies in the way data are collected and presented, and they may not be accessible to those who could use it.

Lack of data and data sharing

The two greatest problems with water quality data are that there is not enough data collected, and what data is collected is rarely shared. There are many different types of water pollution that are inadequately monitored. For example, there are large geographic and temporal gaps in available data on industrial water pollution, limiting assessment of the impacts of industrial facilities and the effectiveness of management strategies. In managing water quality in an agricultural setting, a typical dilemma is the difficulty in determining the extent to which agriculture contributes to the overall water quality problem. A common observation among water quality professionals is that many water quality programmes collect the wrong parameters, from the wrong places, using inappropriate sampling frequencies, and produce data that are often unreliable. Further, the data are often not assessed or evaluated, and are not sufficiently connected to realistic and meaningful programme, legal, or management objectives (Ongley 1994).

Groundwater data are especially limited in scope and availability compared to surface-water data. Some efforts are underway through the International Groundwater Resources Assessment Centre (IGRAC) to expand groundwater information. Moreover, groundwater and surface water are often closely linked hydrologically, making it vital that these data be collected. As UNEP has previously noted, the European Union Framework Directive acknowledges that the scientific community knows far less about the connections between groundwater and surface water than is needed (UNEP 2006). Water data gaps are uneven. Most developing countries lack a sustained long-term local capability in human and technological resources for collecting either local in-situ water quality systems or remotely sensed data.

Limited scope of data

Of the data that do exist, there are limits in what is measured, where, and for how long. Only a few key water quality parameters are consistently measured and even among these, the measurements are limited in duration, geographical scope, and content. Testing is often limited to small number of contaminants and water sources and is infrequent and often voluntary for some users. Fixing these limitations would be vital for any comprehensive water quality programme (see Solutions section, below), but the resources necessary for a truly complete programme are enormous. For example, in the United States there are literally millions of groundwater wells and over 170,000 public water systems. As a result, most programmes rely on a wide range of sources to assess water quality, including routine monitoring, statewide or regional surveys, periodic site-specific studies, and voluntary programmes (DeSimone et al. 2009). Results from these kinds of assessments can help identify critical issues, watersheds, and vulnerabilities for further work. Even the most comprehensive water quality study recently released in the United States reports results from thousands of wells, over nearly a decade of testing, but even so, each well was only tested once, so no time-series data or information are available.

Inconsistent data collection and format

Even some of the most comprehensive water quality programmes in the world suffer from limitations. Many entities collect data using different formats and standards. Data systems are often incompatible or inadequately documented. This makes drawing comparisons and discerning trends in water quality difficult for both surface water and groundwater studies. Conversely, well-collected and well-documented data become more valuable over time for scientists and policy makers.

Overlapping or conflicting jurisdictions complicates the ability to collect consistent and useful long-term data. In many parts of the world, different countries or political entities share watersheds and these jurisdictions may have very different institutional arrangements for water management. Even in Europe along the Danube or the Rhine rivers, different agencies have assigned conflicting uses to the same river segments; they may use different methods or instruments for monitoring; and there is no single agreed-upon standard for the time frame or frequency of water quality monitoring. In the United States along the Mississippi River, monitoring programmes (run by the USGS and the U.S. Army Corps of Engineers) have diminished over the past decade. In general, the scope and quality of biological, physical, and chemical data vary along the Mississippi. The lack of such consistent programmes, data formats, and collection protocols hinders the effective application of the water policy, and makes it more difficult to maintain and improve water quality along rivers and in receiving waters around the world, including estuaries and bays (US NAS 2009).

Inadequate access to data

Access to reliable and useful data and information is vital to achieving improvements in actual water quality. Open access to data is key, but in the past, concerns from data providers regarding use of data have limited some access. One solution, implemented by GEMS/Water, has been to launch a global online database (GEMStat, at www.gemstat.org) as an open web service. This database was launched on World Water Day, March 22, 2006, at the World Water Forum in Mexico and a new advanced system should be available in 2010. GEMS/Water also provides supporting software (GEMSoft) to help maintain data availability and quality. Such open databases are vital for ensuring access to credible data, the ability to compare data over time and space, and the opportunity to integrate water quality data with other environmental data systems.

New methods for displaying and accessing data are being explored. As one example, GEMStat monitoring stations can be mapped using Google Earth to permit users to see water quality data combined with details of the monitoring station, local land use information, and more. Water quality is also increasingly being monitored using remote sensing in conjunction with strategic in-situ sampling for validation/verification. Remote sensing can play a crucial role in determining current conditions and in rapid assessment of accidents or extreme events.

Another major problem with access includes management of both in-situ field data and remotely sensed Earth Observation (EO) data. In-situ methods can be time-consuming and expensive and remote sensing is emerging as a new way to greatly expand the ability to collect data and monitor water quality, especially in inland and coastal regions (GEO 2007). The impact of a new satellite or additional land-based or airborne sensors for water research depends on the ability of users to access data in a timely fashion. Water managers and operations decisions require rapid access in order to permit decisions to be made in a timely way. Recommendations from a 2007 remote-sensing workshop on water quality data called for raw data to be released to users within minutes of reception and processed products within two hours (GEO 2007), but this goal is far from being achieved. Improving access to data thus requires that more attention be paid to how data are collected, processed, and archived, and how to ensure open access to appropriate users. Access to data is often also restricted for political or economic reasons. Several countries asked GEMS/Water to agree not to release water quality data as a condition for supplying it to them.

Water quality data at different scales

While water quality problems are ultimately local problems, water quality data are collected at a wide variety of scales and institutions, from the household, local community, or watershed levels to the national and international scale. Many water quality monitoring programmes are deficient for technical, institutional, financial, or political reasons. Water quality is monitored in different ways in different regions, and no comprehensive dataset, format, or network is accepted as the standard. Perhaps the best current example of a comprehensive global network on water quality is the GEMS/Water network.

The GEMS/Water network (www.gemswater.org and www.gemstat.org), for example, now totals over 1,500 regularly reporting stations (see Table 4 and Figure 6); over 3,200 stations provide at least some data. The number of countries participating in collecting and sharing data is slowly growing over time. When GEMS was launched, few countries collected or reported water-quality data. The 2003 World Water Development Report included a section on problems with water-quality data and led to an effort to expand the GEMS/Water programme from fewer than 40 countries to

Table 4. Countries participating in GEMS Global Data Activities. *Source: http://www.gemswater.org/global_network/index-e.html*

Continent	Number of countries participating	Countries
Africa	11	Burundi, Democratic Republic of Congo, Gambia, Ghana, Kenya, Mali, Niger, Senegal, South Africa, Uganda, Tanzania.
Americas	14	Argentina, Bolivia, Brazil, Canada, Chile, Colombia, Cuba, Ecuador, Guatemala, Mexico, Panama, Peru, United States of America, Uruguay.
West Asia/ MENA	12	Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Libyan Arab Jamahiriya, Pakistan, Morocco, Saudi Arabia, Sudan, Tunisia.
Europe	22	Austria, Belgium, Denmark, Finland, France, Germany, Luxembourg, Greece, Hungary, Ireland, Italy, Lithuania, Netherlands, Norway, Poland, Portugal, Russian Federation, Spain, Sweden, Switzerland, Turkey, United Kingdom.
S.E. Asia	10	Bangladesh, Cambodia, India, Indonesia, Lao People's Democratic Republic, Nepal, Pakistan, Sri Lanka, Thailand, Vietnam.
E. Asia/ Pacific	11	Australia, China, Fiji, Hong Kong, Japan, Republic of Korea, Indonesia, Malaysia, New Zealand, Philippines, and Papua New Guinea.
Other participation	26	
TOTAL	106	

over 100 today (see Table 5). Despite these improvements, data coverage is still incomplete in the vast majority of regions and countries.

Types of water quality data

Thousands of different water quality parameters can be used to identify the quality of freshwater systems. These include hydrological, chemical, physical, biological, and radiological parameters. No assessment can test for all contaminants, nor is there epidemiological health information about the importance, or the risk levels, for most contaminants. As a result, any water quality programme must necessarily choose what subset of parameters to measure based on expectations, known risks, preferred levels of safety, and other economic, social, ecological, and political factors. Table 5 summarizes some of the water quality data parameters collected under the GEMS/Water programme.[7]

Table 6 shows the extent of data collection under GEMS, with the number of stations being monitored, the kinds of physical, chemical, and biological data collected, and the dates of the data collection.

Kinds and scope of water quality data assessments

Few comprehensive water quality assessments on a large scale have been completed. For example, the 2009 EU Water Initiative Summary focuses on water supply, use, and management. It does not discuss water quality data or conditions at all, and only contains the word "quality" three times. The EU Water Directive does require Member States to ensure that monitoring programmes are in place and that the programmes achieve some standard outcomes, including the kinds of parameters monitored, the methods used for analysis, and the frequency of sampling. Member States are also required to ensure that discharges from urban wastewater treatment plants and the quality of receiving waters are monitored.

In comparison, most water quality is evaluated at a local or national level. Individual countries perform water quality

[7] GEMS/Water participation is voluntary and the types and extent of data submitted are at the discretion of the contributor. While contributors have historically been national-level organizations, GEMS/Water is increasingly receiving data from universities and non-governmental organizations, a trend it encourages.

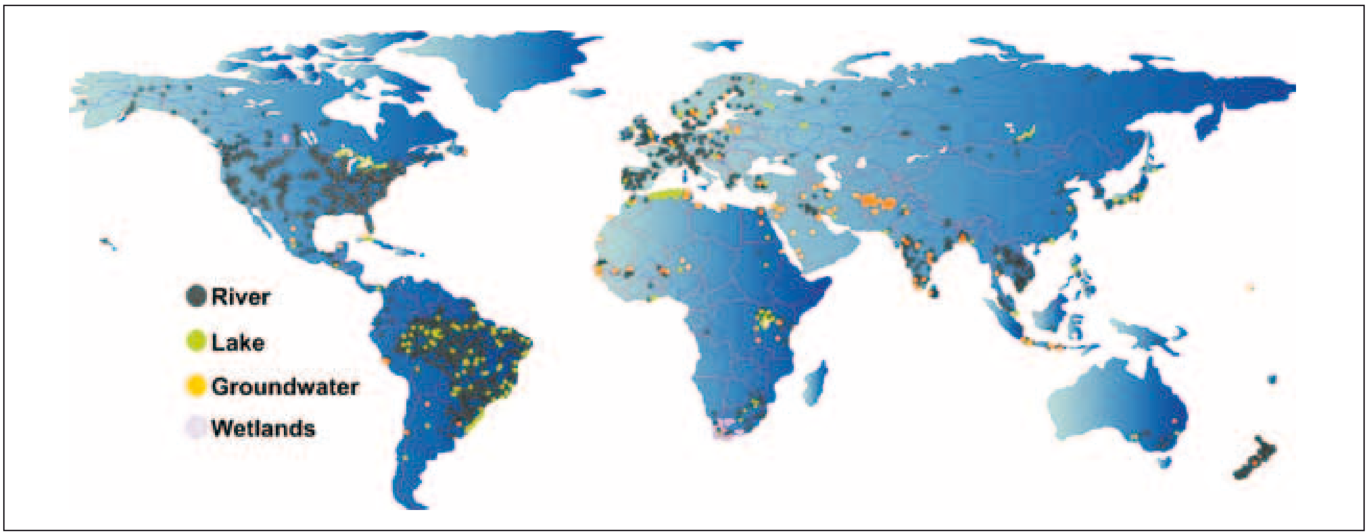


Figure 6. GEMS/Water stations map. *Source : Personal communication, GEMS/Water, February 10, 2010*

evaluations on an occasional or systematic basis. In the United States, water quality monitoring falls under many jurisdictions, from local water agencies that must monitor the quality of drinking water, to industries that must monitor water quality discharges, to national agencies that do systematic and large-scale water quality assessments region- or nationwide. For example, the U.S. Geological Survey (USGS) began the NAWQA (National Water Quality Assessment) programme in 1991 to collect a wide variety of chemical, biological, and physical water quality data from water basins across the nation. (US Geological Survey 2009a)

Among the data collected are:

- Chemical concentrations in water, sediment, and aquatic organism tissues and related quality-control data (from USGS National Water Information System – NWIS);
- Biological data on stream habitat and community data on fish, algae, and invertebrates;
- Site, well, and spatial data like land use, soils, population density, and more; and

Table 5. GEMS water quality parameters. *Source: http://www.gemswater.org/global_network/index-e.html*

Human health/ drinking water	Agriculture	Municipal/ industrial	Ecosystem stability, structure & health	Tourism & recreation
Total coliform	Nutrients	Bod	Temperature	Parasites
Faecal coliform	Nitrogen	Cod	Ph – acidity	Pathogens
Pathogens	Phosphorus	Heavy metals (particularly in sediments)	Conductivity	
Pops	Salinity		Major ions	
Turbidity	Chlorophyll a pathogens		Oxygen	
			Suspended solids (including bed-load sediment quality data)	
			Biodiversity and biomonitoring data	

Table 6: GEMS: Kinds of data, numbers of stations, and scope of water quality data collection. *Source: GEMS/Water Personal communication, February 10, 2010*

Region	Physical/ chemical	Nutrients	Major ions	Metals	Organic matter	Organic contaminants	Micro-biology	Hydrological & sampling variables	Date range
Africa	71390	75185	109179	10177	6936	1915	4944	313	1977-2009
Americas	200027	225285	243512	309377	40845	594622	21482	13567	1965-2008
Asia	225461	123056	154472	87351	49340	8817	40572	12373	1971-2009
Europe	258024	150907	140908	197636	74495	32537	40672	66846	1978-2008
Oceania	241514	101871	11160	3199	14344	1438	10166	20462	1979-2009
Total	996416	676304	659231	607740	185960	639329	117836	113561	1965-2009

- Regular stream flow and temperature information for repeated sampling sites (also from NWIS).

At selected surface-water and groundwater sites, the USGS maintains instruments that continuously record physical and chemical characteristics of the water including pH, specific conductance, temperature, dissolved oxygen, and percent dissolved-oxygen saturation. The most recent data come from around 2,800 stream sites and 5,000 groundwater wells. In addition, the programme collects data on nutrients, pesticides, and other contaminants. In order to make the data available, the USGS has developed a data "warehouse" to store, manage, and distribute water quality data to researchers and the public (USGS STORET 2009a). This "STOrage and RETrieval Data Warehouse" serves federal agencies, states, tribes, environmental groups, community organizations, and universities. The STORET Warehouse encourages data-sharing across jurisdictional and organizational boundaries. As part of this effort, an updated Water Quality Exchange (WQX) provides a framework that permits water quality data to be added on a regular basis by a wide variety of users (USGS STORET 2009b).

A completely different water quality programme in the United States is run by the U.S. Environmental Protection Agency (EPA). The Watershed Assessment, Tracking, and Environmental Results (WATERS) programme is an integrated information system for the nation's surface waters. The EPA Office of Water manages diverse programmes in support of water quality. Many of these programmes collect and store water quality data in databases. These databases are managed by the individual water programmes and this separation often inhibits the integrated application of the data they contain. Under WATERS, the Water Programme databases are connected to a larger framework. This framework is a digital network of surface water features, known as the National Hydrography Dataset (NHD). By linking to the NHD, information can be shared across programmes. Table 7 shows examples of water quality programmes at the U.S. national level.

In the U.S., the National Water Quality Monitoring Council and the Advisory Committee on Water Information recently proposed the following common elements for water quality data:

- Point of contact information – identify who collected and analyzed the sample.
- Results – report what was analyzed and the resultant measurement.
- Reason for sampling – explain why the sampling was undertaken and sampling design used.
- Date/time – record when the sample was collected.
- Sampling station location – record where the sampling occurred.
- Sample collection and analysis – describe methods for sample collection and laboratory analysis.

Governance and regulation

Water governance refers to the range of political, social, economic, and administrative systems that have developed to allocate and manage water resources, and to implement the water quality solutions discussed above. The term governance includes "the mechanisms, processes, and institutions through which all involved stakeholders, including citizens and interest groups, articulate their priorities, exercise

Table 7. Examples of diverse water quality programs at the U.S. National level. *Source: U.S. EPA Office of Water website, 2009*

Office of Water Program	Program Database	Description
Water Quality Standards	WQSDB	The Water Quality Standards Database (WQSDB) contains information on the uses that have been designated for water bodies. Examples of such uses are: drinking water supply, recreation, and fish protection. As part of a State's water quality standards, these designated uses provide a regulatory goal for the water body and define the level of protection assigned to it. WQS also includes the scientific criteria to support that use.
Integrated reporting 305(b) Report and 303(d) List	ATTAINS	The Assessment, TMDL Tracking and Implementation System (ATTAINS) database contains information reported by the states to the EPA about the conditions in their surface waters. The database is comprised of information on the attainment of water quality standards; as well as the list of impaired waters that need a Total Maximum Daily Load (TMDL).
Water Quality Inventory 305(b) Report	NAD	The National Assessment Database (NAD) contains information on the attainment of water quality standards. Assessed waters are classified as Fully Supporting, Threatened, or Not Supporting their designated uses.
Total Maximum Daily Load (TMDL) 303(d) List	TMDL Tracking System	The Total Maximum Daily Load (TMDL) Tracking System contains information on waters that are Not Supporting their designated uses. These waters are listed by the state as impaired under the Clean Water Act. The status of TMDLs is also tracked. TMDLs are pollution-control measures that reduce the discharge of pollutants into impaired waters.
Water quality monitoring	STORET	STORET (short for STOrage and RETrieval) is a repository for water quality, biological, and physical data and is used by state environmental agencies, EPA, and other federal agencies, universities, private citizens, and many others. The Legacy Data Center, or LDC, contains historical water quality data dating back to the early part of the 20th century and collected up to the end of 1998.
NPDES Permits	PCS	Discharge of pollutants into waters of the United States is regulated under the National Pollutant Discharge Elimination System (NPDES), a mandated provision of the Clean Water Act. To assist with the regulation process, state and federal regulators use an information management system called the Permit Compliance System (PCS). PCS stores data about NPDES facilities, permits, compliance status, and enforcement activities for up to six years.
Safe Drinking Water	SDWIS	The Safe Drinking Water Act (SDWA) requires that states report to the EPA information about public water systems and their violations of EPA's drinking water regulations. These regulations and their enabling statutes establish maximum contaminant levels, treatment techniques, and monitoring and reporting requirements to ensure that water provided to customers is safe for human consumption. This information is stored in SDWIS – Safe Drinking Water Information System.
Fish Consumption Advisories	NLFWA	The National Listing of Fish and Wildlife Advisories (NLFWA) database includes all available information describing state-, tribal-, and federally issued fish consumption advisories in the United States and Canada.
Nonpoint Source Pollution	GRTS	The Grants Reporting and Tracking System (GRTS) is the main reporting vehicle to help EPA and States describe the progress they have made in implementing the national Nonpoint Source (NPS) Pollution program. GRTS electronically tracks projects and activities funded with CWA funds.
Nutrient Criteria	Nutrient Criteria Database	The Nutrient Criteria Database stores and analyzes nutrient water quality data to aid in the development of scientifically defensible numeric nutrient criteria. The ultimate use of the data is to derive ecoregional water-body-specific numeric nutrient criteria.
BEACH program	BEACH Watch	The Beaches Environmental Assessment, Closure & Health BEACH Watch database provides information on whether a specific beach is being monitored for water quality, who is responsible for the monitoring, the pollutants that are being monitored, and if advisories or closures have been issued.
Vessel Sewage Discharge	NDZ	Vessel sewage discharge is regulated under the Clean Water Act, which mandates the use of marine sanitation devices (on-board equipment for treating and discharging or storing sewage) on all commercial and recreational vessels that are equipped with installed toilets. Under U.S. law States may request a No-Discharge Zone (NDZ) designation that prohibits the discharge of sewage from all vessels into defined waters.
Clean Watersheds Needs Survey	CWNS	The Clean Watersheds Needs Survey (CWNS) provides information on publicly owned wastewater collection and treatment facilities; facilities for control of sanitary sewer overflows (SSOs); combined sewer overflows (CSOs); stormwater control activities; nonpoint sources; and programs designed to protect the nation's estuaries. Information obtained from the survey is maintained in the CWNS database.

their legal rights, meet their obligations, and mediate their differences" (UNDP-WGF). Governance has been defined as a range of systems which determines *who* gets *what* water, *when* and *how*. Water governance, in particular, includes international water agreements and national legislation (e.g., water quality standards); the implementation of policy and associated institutions (e.g., monitoring and enforcing standards); and the participation of civil society and the private sector (e.g., stakeholder involvement).

There is a water crisis, and there is an increasing understanding that it is a crisis of governance rather than one of physical scarcity of water. Water pollution and scarcity are, to a large extent, social and political challenges. Sustainable water management is about how individuals, as part of a collective society, govern water resources and their benefits. The lack of good governance, including ineffective policies, enforcement, and institutions; corruption; and the lack of appropriate infrastructure, along with a shortage of new investments in building human capacity, all contribute to ongoing water quality problems.

Weak institutions, inadequate water quality policies and regulations, and limited enforcement capacity underlie many water quality problems worldwide. Many countries – particularly in the Global South – have little-to-no policy framework to protect water quality. However, even in countries with comprehensive policies and regulations, water quality is not protected unless the regulations are effectively implemented. Overall, there is a persistent and pervasive lack of investment in the institutional capacity necessary to establish, monitor, and enforce water quality policies.

Ineffective regulations can result in inequitable distribution of water pollution and its impacts. In the absence of effective and well-enforced regulations, there are often short-term economic incentives for industries to pollute, because the costs of this pollution are typically borne by other parties. At a global scale, differences in the stringency of water-pollution regulations can cause high-polluting industries – and their impacts – to concentrate in countries with weak regulations. In general, many industries are moving from high-income countries to emerging market economies, leading to severe environmental and human health concerns and often hindering future economic development (UN WWAP 2009).

Water reforms (cases)

At the turn of the 21st century, several large-scale water governance reforms were enacted in order to address growing pressures including environmental degradation, growing human water demands, and global climate change. South Africa, Australia, the European Union, and Russia have all passed innovative legislation designed to fundamentally re-work their approaches to water management. Because of the varying characteristics of water resources and political frameworks, governing mechanisms vary considerably across these countries. Yet despite these variations, all three reforms include components linked to:

- Recognition of declining ecosystems and persistent water quality problems;
- Decentralized water decision making;
- Increased stakeholder participation;
- Clarification of institutional roles and responsibilities, such as through formal legislation and changes in water rights; and
- User-pays and polluter-pays principles.

South Africa

South Africa was at the vanguard of water reform efforts – it was one of the first to engage in significant water reform, passing National Water Act in 1998, four years after the end of apartheid. The Act was lauded as a progressive piece of policy, with the redress of past injustices as one of its overarching aims (Movik 2009). In addition, the Act embodied the recognition that "nature" must have a "water right" if the natural environment was to continue to support and sustain human endeavors: the "Reserve," which refers to both an ecological reserve that requires a minimum level of instream flow to ensure ecosystem sustainability, and a human reserve, which requires quantities of water necessary to meet basic human needs. This Reserve must be met before other uses can be satisfied.

The Act also created compulsory national water quality and supply standards, standard water tariffs, and regulations for water services providers to follow in order to provide a framework for local government to provide efficient, affordable, economical, and sustainable access to water services. The rules support the principles contained in both the Constitution and the Act, and help to give meaning to the right of access of all people to a basic level of clean water provision.

In terms of management, the country was partitioned into 19 water management areas based on drainage regions, to be governed by Catchment Management Agencies. The purpose of the agencies was first and foremost outlined as "coordinating and promoting public participation in water management" (Anderson 2005), though it was envisaged that these responsibilities could be expanded to include setting and collecting water-use charges and issuing water-use licenses (Schreiner and Van Koppen 2002).

Despite these reforms, data from 2004 showed that less than 50 percent of water service providers had drinking water quality monitoring programmes in place. In 2005, the Drinking Water Quality Regulation programme was established, requiring microbial and chemical water quality testing and setting compliance standards. The government also developed the "Blue Drop" status, which is awarded to water service providers who are at or above 95 percent compliance with standards. In 2009, 100 percent of the municipal authorities had water quality monitoring programmes in place, though only 18 municipalities have been awarded Blue Drop status out of over 150 municipalities.

Australia

In Australia, rising water diversions for agricultural and urban use have been accompanied by emerging environmental problems in the region, including toxic cyanobacterial blooms, decreased water quality, loss of wetlands, and high soil salinity. Over the last decade, these issues have been exacerbated by prolonged drought and emerging climate change impacts. Between 2006 and 2008, the country's main agricultural region, the Murray Darling Basin, received extremely low annual precipitation. The 2006 water year had the lowest runoff on record in the Murray-Darling Basin (Figure 7).

Initially, the drought was considered simply one of many in a region that is prone to these events. Scientists now believe that these recent events in Australia are a harbinger of long-term climate change. Indeed, Australia's Bureau of Meteorology predicts that within two-to-three decades, drought will occur twice as frequently and be twice as severe (Schneider 2009). In 2007, Australia commenced reform of its water management system to incorporate this new, water-scarce reality, passing the Commonwealth Water Act. The Act and accompanying intergovernmental agreements have seen Constitutional rights over water resources in the Murray-Darling Basin assigned by the States to the Commonwealth and investment of approximately $13 billion Australian dollars (~US$ 10.5 billion) in water reform measures including:

- federalizing water data collection;
- requiring greater regulatory reporting (e.g., water balances and a National Water Account);
- moving to full cost recovery for all water infrastructure and services;
- creating a market for water trading (based on tradable property rights and in combination with a review of existing caps on water extractions);
- increasing on-farm efficiencies (e.g. canal lining, drip irrigation, shifting to more water-efficient crops); and
- purchasing water entitlements from willing sellers to restore aquatic ecosystems.

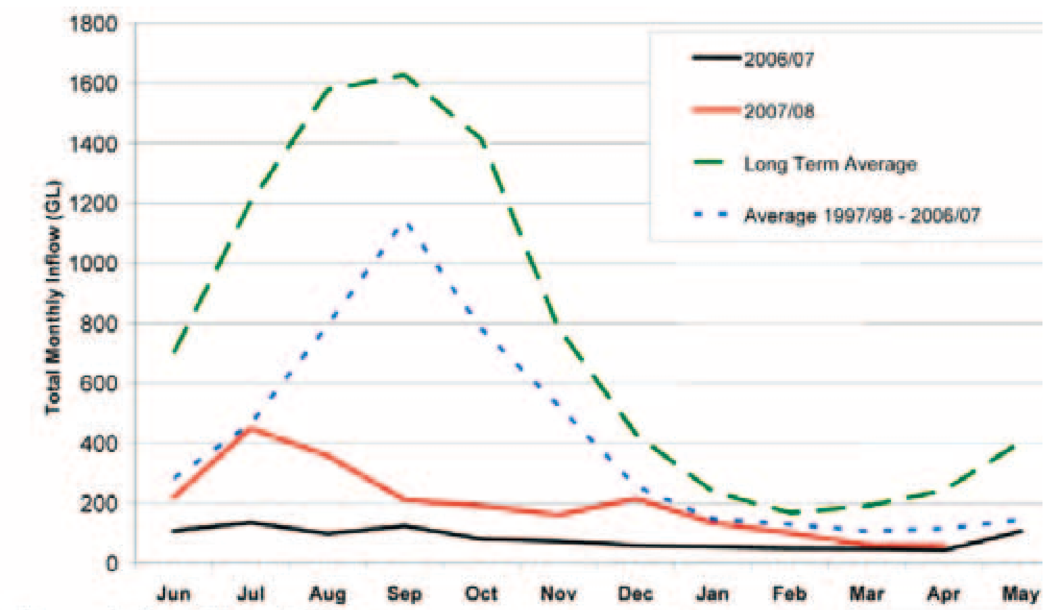


Figure 7. Monthly inflows into the Murray River system. *Source: Craik and Cleaver, 2008*

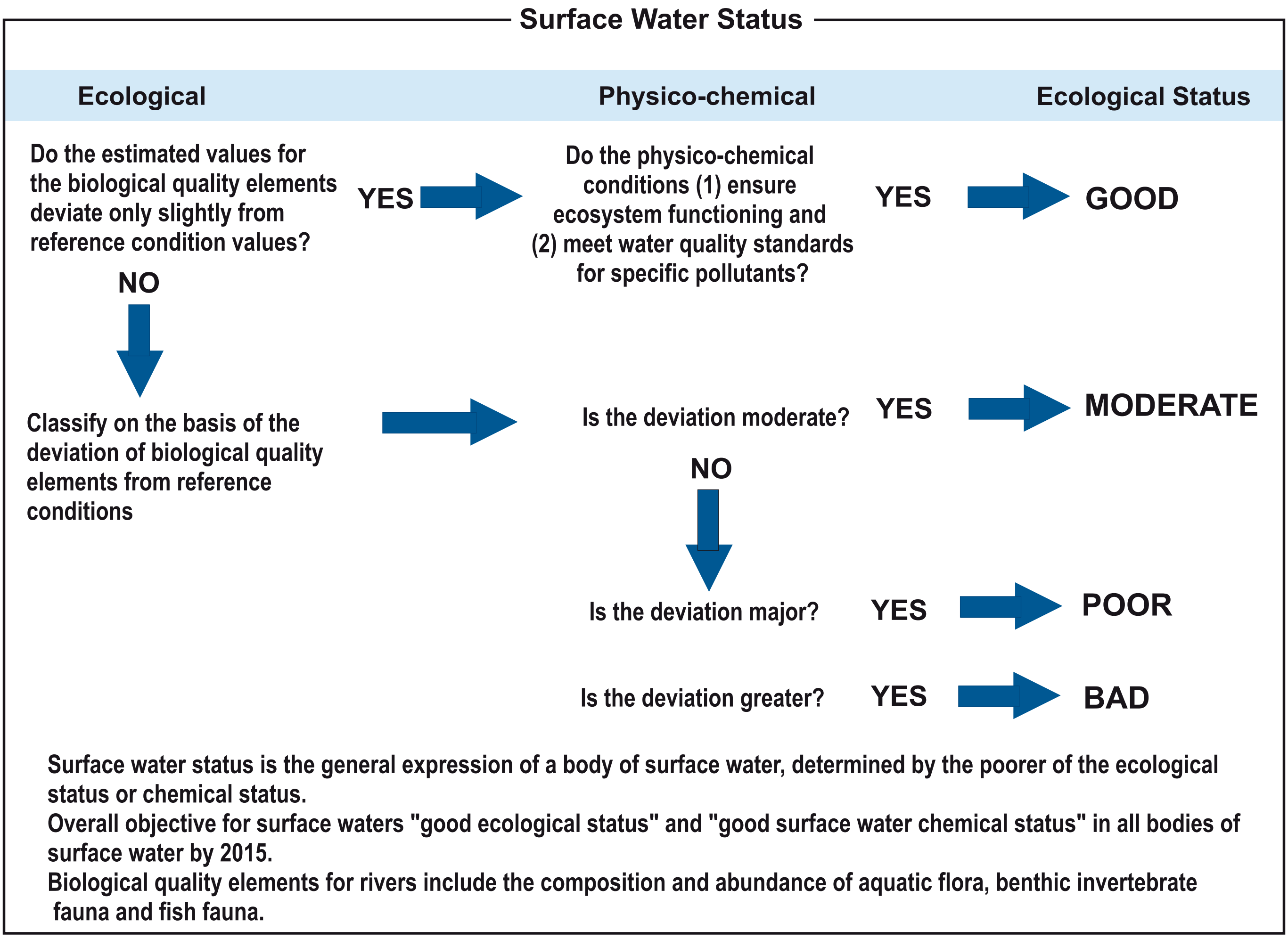


Figure 8. Summary of the decision tree used to classify the status of surface water bodies.

Australia's water reform has been closely tied to increasing the efficiency of water use, largely through a water rights market. However, it has also created a new federal repository of water monitoring and measurement information. These data are critical for adequate water quality and quantity protection.

European Union

The European Union Water Framework Directive was passed in 2000. The directive re-wrote and centralized water policy for member states into one piece of legislation that encompasses three main issue areas, which had been addressed separately in the past. The "three pillars" of the legislation are: ecology (all water bodies must reach "good" ecological status by 2015); governance (new water management authorities were created at the river basin scale and were charged with more participatory decision-making); and economy (water suppliers should aim for full cost recovery and begin economic analyses to charge the "true cost" of water by 2010).

Each pillar has its own series of measures to be enacted within a specific timeframe. Beginning with the ecology pillar, the directive set the target of "good" ecological status and established a decision-making process to determine whether surface and groundwater bodies are in bad, poor, moderate, or good status. In order to attain "good" status, the physical-chemical, hydro-morphological, and biological elements must show very slight-to-no alterations from reference conditions (reference areas are chosen to reflect a lack of human disturbance). A summary of the process to define surface water status is provided below (Figure 8). After characterizing all of the water bodies within a river basin district, river basin authorities are responsible for setting up monitoring programmes, establishing a series of objectives and measures to achieve "good" status, and inscribing these in a river basin management plan.

The directive requires member states to designate "Competent Water Authorities" (Article 3) for implementation of river basin characterization and management plans. Competent authorities must ensure coordination among all stakeholders and bodies concerned with water management in order to draft these plans. In addition, the WFD insists on the active involvement of all interested parties in the production, review, and iterative updates of the river basin management plans (Article 14). This primarily involves consultation rather than active participation as the directive states that member states shall "publish and make available for comments to the public a timetable and a work programme, ...an interim overview of the significant water management issues, ...draft copies of the management plan" (Article 14). For each step, the public has at least six months to comment in writing on those documents and, on request, access shall be given to background documents and information.

In contrast with the narrow ecological definitions of the legislation, the very broad definitions of governance procedures may lead to widely different interpretations and implementation in member states. Depending on institutional and political contexts, competent authorities may be national bodies, e.g. the Environment Agency in England and the National Institute of Water in Portugal, or more local ones, e.g., hydro-geographical water agencies in France. In many ways, the directive leaves the governance issues flexible in order for member states with very different socio-political contexts to determine how they will organize implementation to achieve the goals (Grantham et al. 2007).

The directive also calls for an economic analysis of water uses in each river basin district. This economic analysis is necessary to make the relevant calculations necessary for taking into account the principle of cost recovery, using estimates of volume, prices, and costs of water services; estimates of present and forecasts of future investments; and estimates of the social, environmental, and economic effects of recovery. The analysis should also take into account long-term forecasts of supply and demand for water in the river basin district in order to make judgments about the most cost-effective combination of measures to inform the Programme of measures (Article 11) and River Basin Management Plan (Article 13).

Russia

More recently, in 2006, Russia re-wrote its water code (Russian Federation Water Code No. 174-ФЗ) to focus on integrated regional water management. The code's founding principles are that protection of water bodies (both surface and ground) takes priority over use, that usage shall not harm the environment, and that utilization be prioritized toward drinking and other domestic purposes (Simpson 2007). Some of the code's innovations include its river basin approach, the introduction of integrated water basin management schemes, and civil society involvement in decision making.

In terms of water quality, the code sets maximum allowable concentrations of chemicals, nuclear substances, microorganisms and other water quality indices. These norms are developed by responsible federal executive authorities for each water basin. For water bodies that are used for drinking water supply, special pollution prevention zones are established. A system of regulations and bans are established for sewage discharges, along with dumping and discharges of harmful substances. In addition, a monitoring system is established, organized at the water basin level, to provide for regular observations on water quality and quantity, regimes of water use, data processing, and updating of a state water register. The state water register, to which there is free access (Article 31), is a compilation of documentation on water bodies and water basins, water quality and quantity, water use, hydro-technical facilities, and water protection zones. It also assembles the agreements and decisions on water use.

Policies, laws, and regulations

The extent to which water quality is regulated varies widely among different countries and regions – ranging from no water pollution control regulations (e.g., Myanmar) to a comprehensive policy framework and regulations (e.g., the European Union's Water Framework Directive, 2000/60/EC). A strong policy framework is an essential first step in effectively regulating water quality. Lack of a comprehensive approach has often led to costly and ineffective water policies. For example, a review of water policies in several East and West African countries found that "water quality is affected by a number of other activities such as sanitation, solid and liquid waste disposal; if the laws governing these are not concurrently formulated and rationalized with other existing national laws, management of water quality will remain difficult" (MetaMeta/ODI 2006). These types of challenges led to the development and increasing application of an integrated water resources management approach (IWRM). IWRM requires an examination of biophysical and socioeconomic linkages such as those that exist between separate sectors (e.g., industry and environment) and between upstream activities and downstream impacts.

> "Integrated water resources management is a process which promotes the coordinated development and management of water, land, and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP-TAC 2000).

Good, enforceable regulations must follow creation of an overall water quality policy. Poorly designed or out-of-date regulations will fail to adequately address water quality issues. For example, a recent review of surface water quality regulations in Eastern Europe, Caucasus, and Central Asia countries found that while the countries all had water quality regulations, most of their lakes and rivers were considered to be "moderately polluted." Many surface-water quality standards contained in these regulations were out-of-date and were unrealistically stringent given the government's limited capacity to monitor and enforce the standards (EAP Task Force Secretariat 2008). Institutional and investment limitations will be discussed further in the next section.

In addition to regulating water pollution directly, regulating and reducing the use of contaminants themselves can be an effective preventative approach to water quality improvement. The European Union recently revised its chemical control regulations to improve identification and mitigation of health risks. The new policy, known as Registration, Evaluation and Authorization of Chemicals (REACH) places the burden on chemical companies to ensure that chemicals do not pose a risk to human or environmental health (GAO 2007).

Establishing water quality standards

Establishment of specific, binding water quality standards can assist efforts to improve water quality by increasing accountability for implementation of pollution-control measures and overall water quality monitoring. Binding water quality standards are generally established at the national level, although supranational standards exist as well, such as the Water Framework Directive in Europe. Many countries have established drinking-water quality regulations to safeguard human health.[8] For example, in the United States, contaminant levels in drinking water are regulated by the Safe Drinking Water Act, and WHO reports that three-quarters of countries in their African Region and more than three-quarters of countries in their South East Asian region have national drinking water standards (WHO-Africa 2000, WHO-SEA 2003). The European Union (EU) has established drinking water contaminant-level standards for member countries (Council Directive 98/83/EC). These standards help to ensure that drinking water is safe for human consumption.

Standards for surface water quality have also been implemented in many countries. These types of standards can be in the form of limits on contaminants in wastewater effluents, or ambient water contaminant limits. Regulation of groundwater quality is less common, but groundwater quality standards have been established in some countries. The Water Framework Directive in Europe established Environmental Quality Standards for 33 pollutants in surface, ground, and coastal waters (Directive 2006/7/EC). It also set standards for discharges of nitrogen and phosphorus from urban wastewater treatment plants into sensitive water bodies (Directive 98/15/EEC).

International water quality guidelines

International water quality guidelines can help to establish similar levels of protection of water-related human and environmental health in all countries, and assist countries in developing enforceable water quality standards. For example, guidelines for drinking water contaminant levels have been developed by the World Health Organization (WHO 2008). Many countries set drinking water standards based on these guidelines, modified to reflect what is economically and technologically achievable in a country (Carr and Neary 2008). The guidelines reduce the amount of evaluation, cost-benefit analysis, and research that needs to be done by a country when creating drinking water regulations, as it already contains information on what levels of various contaminants can be considered safe for human consumption. Furthermore, these can be used as interim guidelines before or while a country is in the process of developing national standards.

Various other international guidelines exist that can similarly aide countries in developing regulations. To preserve agricultural production and soil conditions, the Food and Agriculture Organization (FAO) has issued quality guidelines for irrigation water (Wescot and Ayers 1984). FAO also gives guidelines for water quality for livestock and poultry, meant to safeguard the health of the livestock and people consuming associated meat or dairy products. WHO has established health-based targets for contaminants in wastewater used to irrigate crops or used in aquaculture (WHO 2006b). Similarly, standards outlining sampling, terms, measurement, and reporting of water quality, as well as definitions and measurement of service activities in the drinking and wastewater sectors, have been developed by ISO (ISO 2009).

No international guidelines for ecosystem water quality exist, and GEMS/Water notes that:

> 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

[8] For an overview of drinking water standards by country, see Carr and Neary 2008.

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 (UNEP GEMS/Water 2006a).

Establishment of such ecosystem water quality guidelines could help to streamline and expedite the integration of ecosystem considerations in water quality regulations world-wide.

International governance and law

The development of water quality goals and policies at the international level, for example through UN meetings, conferences, and summits and World Water Forums, guide and support national efforts. Efforts of the United Nations and other international organizations such as NGOs are important to help build political will across the globe to address water quality issues, as well as provide technical, financial, and other support to build capacity and develop effective solutions to water quality challenges (Figure 9).

Managing transboundary waters

Rivers, lakes, and groundwater aquifers that cross political boundaries are very common; basins shared by two or more nations cover about half of the earth's land surface and are relied upon by around 40 percent of the world's population (Wolf et al. 1999). Transboundary basins require cooperative management to ensure that the resource is shared fairly among basin countries. Management of water quality, particularly through pollution prevention and up-stream pollution control, is important to ensure that downstream countries are not unfairly burdened with pollution originating outside of their borders. Unfortunately, transboundary water pollution is a major challenge in many parts of the world; the Global International Waters Assessment (GIWA) found that "transboundary pollution is the top priority concern in a quarter of all GIWA regional reports, and a further third of the regional reams ranked it as the second most serious concern" (UNEP 2006).

Different types of pollutants have different potentials to cause negative impacts downstream, based on their mobility, ability to accumulate, and persistence in the environment. Persistent organic pollutants are of particular concern because of their long lifetime and potential adverse human and environmental impacts (UNEP 2006). The Ganges-Brahmaputra River system in India receives petrochemical, pesticide, and other factory wastewaters, in addition to sewage and agricultural runoff, before flowing into Bangladesh (IEDS 2003). However, many other types of pollutants also cause transboundary water pollution challenges. In the Black Sea, which has 23 countries in its catchment area, eutrophication caused primarily by agricultural runoff has been identified as the most critical environmental issue. Environmental damage to the Black Sea has resulted in an estimated annual decline in tourism revenues of US$ 360 million (UNEP 2006).

While many international water-management agreements exist, they rarely focus on water quality concerns (Jägerskog and Phillips 2006). This lack of focus on water quality can be problematic for downstream countries. For example, in the 1950s, water in the Colorado River received by Mexico was too saline to be used for irrigation. Extensive negotiations with the U.S., the upstream country, and amendments to the treaty governing allocation of the Colorado River water resulted in the establishment of salinity thresholds for water received by Mexico (Hundley 1966).

Treaties and other international agreements regarding the management of transboundary waters encourage transboundary cooperation and provide a mechanism for creating transboundary support for implementation of water quality solutions. Both general international guidelines and specific bilateral or multilateral treaties exist to guide the management of transboundary waters. Various international guidelines on transboundary water management have existed throughout history, but the ones that are most recent and relevant today are the Convention on the Law of the Non-navigational Uses of International Watercourses (UN Convention) and the Berlin Rules.

The UN Convention was adopted by the UN General Assembly in May of 1997 and is the strongest international instrument regarding transboundary management to date, although it has not been ratified by enough countries for it to enter into force (Salman 2007). It contains a number of principles that are relevant to the management of water quality in transboundary watersheds, including the obligation of states to take all appropriate measures to prevent harm to other states from their use of water, and the obligation of states to cooperate on the basis of equality, integrity, mutual benefit, and good faith in order to optimally use and protect shared watercourses (Cooley et al. 2009).

The Berlin Rules, developed in 2004 by the ILA, are the most recent set of international rules for the management of transboundary waters. These rules are based both on the UN Convention and older international rules, but add emerging concerns including ecological integrity and sustainability and public participation. One important distinction between the UN Convention and the Berlin rules is that the former categorizes harm as only one factor in determining equitable and reasonable use, while the latter explicitly establishes no-harm and reasonable and equitable use as co-equal goals (Cooley et al. . 2009, Salman 2007).

Case study

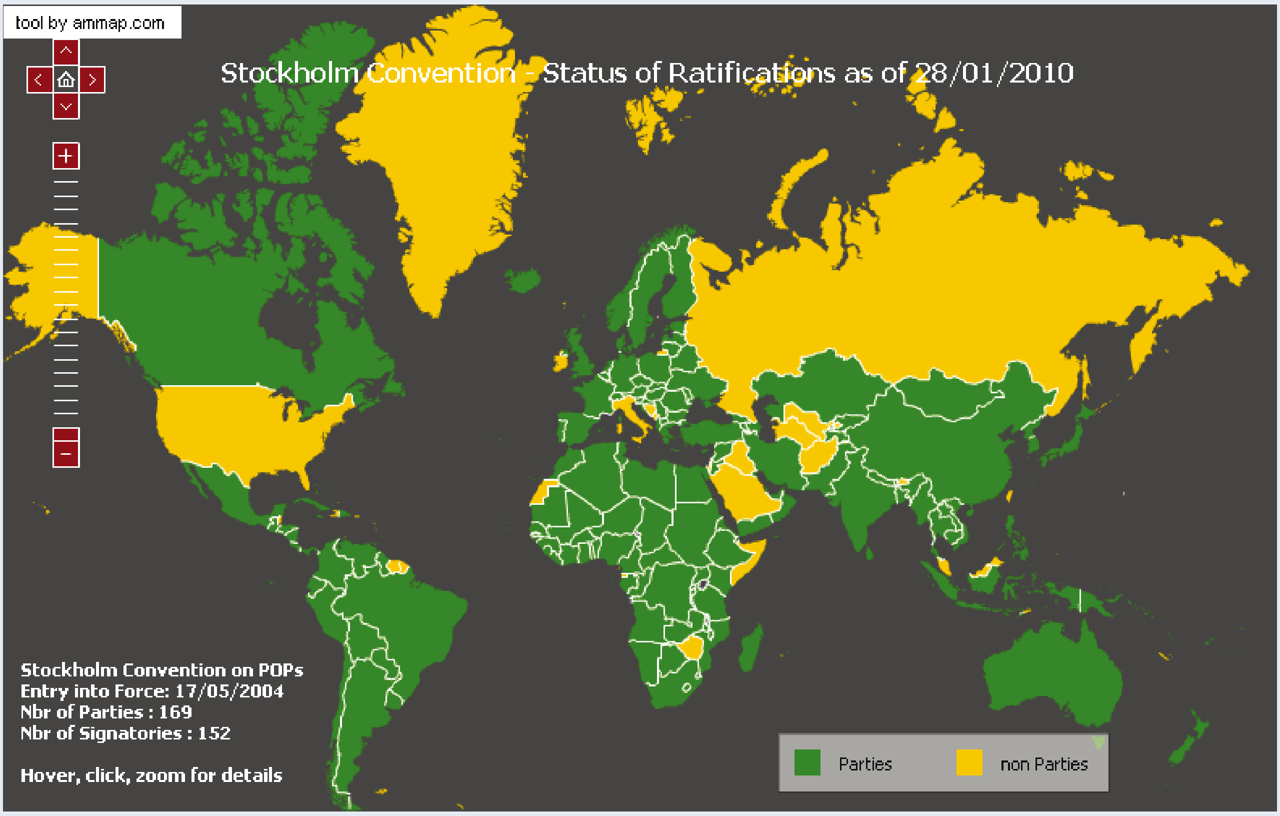
Stockholm Convention on Persistent Organic Pollutants

While there are no enforceable international standards for water quality, there are guidelines developed by the World Health Organization and several international agreements regarding specific water quality issues, e.g., persistent organic pollutants (POPs). POPs are chemical substances like PCB and DDT that persist in the environment and bioaccumulate through the food web. There is evidence of long-range transport of these substances to regions where they have never been used or produced and with the consequent threats they pose to the environment of the whole globe, the international community has now, at several occasions, called for urgent global actions to reduce and eliminate releases of these chemicals (UNEP POPs).

In 2000, after much urging from the United Nations Environment Programme, an intergovernmental negotiating committee reached an agreement on reducing and controlling the discharge of POPs as an international measure with binding force. The draft convention initially targeted 12 substances: aldrin (insecticide); dieldrin (insecticide); endrin (insecticide); chlordane (insecticide); heptachlor (insecticide); toxaphene (insecticide); mirex (insecticide, fire-resistant material); hexachlorobenzene (fungicide); PCB (insulation oil, heat carrier); DDT (insecticide); dioxins; and furans. The convention entered into force in 2004 with ratification by an initial 128 parties and 151 signatories. Signatories agree to outlaw nine of the dirty dozen chemicals, limit the use of DDT to malaria control, and curtail inadvertent production of dioxins and furans.

Parties to the convention have agreed to a process by which chemicals can be reviewed and added if they meet certain criteria for persistence and transboundary threat. Nine new chemicals were added in 2009. As of January 2010, there are 169 parties to the Convention, representing the vast majority of countries (Figure 9).

Figure 9. Status of international ratification of the Stockholm Convention on Persistent Organic Pollutants (parties to the Convention are in green)



In addition, approximately 300 multilateral and bilateral transboundary agreements exist (Gleick 2000, UNEP/OSU 2002) – however, few (4 percent) of the treaties negotiated in the twentieth century focus on water pollution (Jägerskog and Phillips 2006). Integration of water quality concern into transboundary water treaties is a potential mechanism for implementing water quality improvement solutions.

Financing water quality

Securing adequate capital is often a key challenge for institutions. It is expensive to treat water to high-quality standards, to adequately monitor water quality, to analyze the data in order to identify violations, and to enforce standards on the ground. Investing in the expertise and capacity development of water management institutions is a critical first step in order to enable successful water quality regulation. Unfortunately, funding for water treatment, water quality monitoring, and water quality enforcement are inadequate in most countries. According to the Global Water Supply and Sanitation Assessment Report (WHO 2000), countries on average invest far more in water quantity (e.g., supply) than quality (e.g., sanitation).

Of the total annual investment in the water sector, approximately US$ 16 billion, only one-fifth of the total, is directed to sanitation. The fact that only 60 percent of the global population has access to improved sanitation can be explained, in part, by the low level of investment in sanitation when compared with the investment in the water sector as a whole (WHO 2000). For example, due to nonexistent and decaying infrastructure, over 60 percent of wastewater discharges do not meet basic water quality standards in Russia and experts estimate that less than one-half of Russia's population has access to safe drinking water. State representatives say that it will cost US$ 459 billion (15 trillion rubles) to complete necessary upgrades and new construction for water and sanitation infrastructure in Russia by 2020 (Zagden 2009). Russia has taken steps toward reform by passing a new water code in 2006 that, among other measures, institutes a more rigorous polluter-pays and user-pays system to raise revenue for needed water quality treatment and management improvements (for more information see Section III: Governance and Regulation).

As described earlier, investments in water quality concerns are small worldwide in comparison to investments in water supply, and are far below what is necessary to achieve Millennium Development Goals. With estimates that it will cost an additional US$ 2 - $17 billion annually until 2015 to reach water sanitation targets worldwide, it is critical that adequate financial investment and planning tools are brought to bear.

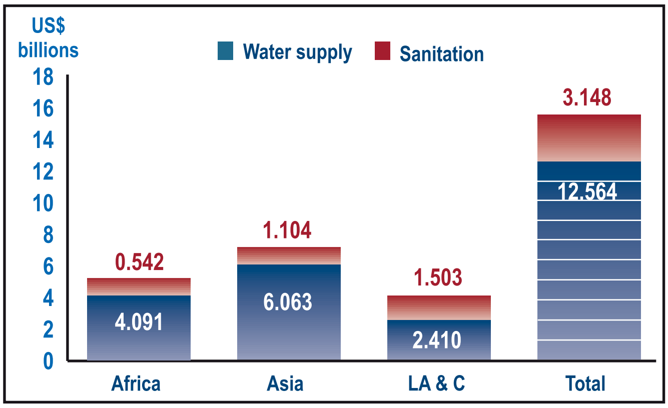


Figure 10. Total annual investment in water supply compared to total annual investment in sanitation in Africa, Asia, and Latin America and the Caribbean, 1990–2000. Source: WHO and UNICEF 2000

Capturing economies of scope

The movement toward more integrated water resource management opens opportunities in terms of financing, as it can capture new economies of scope. An economy of scope exists when a facility or programme that produces more than one kind of product or service is less expensive than two separate facilities or programmes that produce the same quantity of these products or services.

Economies of scope in water systems are the least well recognized economic force behind the growth of an integrated water management paradigm. In the past, the failure to coordinate across functional disciplines was either not very costly or less than the perceived cost of coordinating across functional boundaries. But today, failures to coordinate are very costly and cannot be ignored in most parts of the world. For example, a new dam and reservoir that will destroy significant biological resources and displace thousands or millions of people will be politically opposed, and the trade-off between water supply and goods or services that depend on a free-flowing river will be considered. Similarly, one can no longer relocate water supply intakes upstream of wastewater discharges. Water supply and wastewater planners have been forced by population and urban growth to consider raw water supply and wastewater discharge issues at the same time. If a solution exists that provides additional water supply while also enhancing another type of service (e.g., ecosystem services or local economic development), that solution captures an economy of scope. Solutions that capture economies of scope are increasingly available because technological progress makes some economies of scope easier to capture and water management institutions are becoming more integrated.

Institutional capacity building

Water policies and laws are administered by various institutions at international, national, and sub-national scales. These institutions are responsible for implementing often broadly written policy language, which may require developing specific regulations and standards along with monitoring and enforcement. The scale, structure, and scope of water-related institutions varies both within and between countries from local, to catchment, to national scales; from participatory councils to hierarchical bureaucracies; and from single purpose missions, e.g., wastewater collection and treatment, to integrated management, e.g., river basin management entities with authority over land and water use.

The success of water-pollution-control efforts depends, in large part, on the effectiveness of these institutions, which in turn depends on the availability of capital, expertise, political will, and enforcement mechanisms. For example, countries with social or political instability often lack the resources or political will to implement and enforce water quality regulations, and some (e.g., Congo, Afghanistan, Kazakhstan) lack even basic drinking water standards (UNEP GEMS/Water 2008). It is now widely recognized that it is most often these social factors, rather than technical problems, that cause failures in the protection of water quality.

Strengthening enforcement

While clear, comprehensive, and enforceable standards are a key solution to persistent water quality challenges, they are only the first step. In order for them to be implemented adequately, proper monitoring and enforcement are crucial. In terms of monitoring, appropriate measurements need to be taken in the right places and at the right times in order to be able to even understand whether a standard is being met (see section on data and monitoring). If it is determined that a standard has been or is being violated, it is then necessary to have efficient enforcement procedures to stop the violation and then take punitive action.

The way that countries implement and enforce policies varies greatly. However, most democratic countries have a legal system that can impose fines using existing court infrastructure on a local or provincial level. In addition, withholding public funds can be another strategy, since in many cases both public and private sector polluters rely on some form of public funding whether it is through direct loan programmes or through partial public funding for infrastructure, etc. Regulations that establish water quality

Case study

Building capacity for compliance with environmental regulations in the Danube River basin

The Danube River, located in Central Europe and shared by 18 countries, has been badly polluted by industrial and other wastes. An assessment of the river in 1999 found that it contained hazardous substances, microbial contamination, and high nutrient loads which led to eutrophication (Vousden 2007), and identified 130 major industrial polluters in 11 countries (IW LEARN TEST). To address this pollution, the United Nations Industrial Development Organization (UNIDO) started a Transfer of Environmentally Sound Technologies (TEST) project on the river in 2001. The TEST program aims to build capacity in industrial service institutions to identify the least costly method for complying with environmental regulations through mechanisms such as cleaner production, environmental management systems and accounting, and selection of environmentally sound technology (UNIDO TEST).

The project on the Danube River was intended to demonstrate that environmental targets can be met while maintaining or even improving economic productivity and competitiveness, and to bring the selected industrial polluters into compliance with both European Union Accession and the Danube River Protection Convention requirements. More than 90 employees were trained to use the TEST approach, and over 230 cleaner production measures were implemented (UNIDO TEST).

The project was largely a success, not only reducing water pollution, but resulting in a number of benefits to the companies, including reduced fines; reduction in costs associated with wastes (including through the recycling of wastes); better product quality; and marketing opportunities (Vousden 2007).

Case study

Funding enforcement through pollution fines in Colombia

The region of Eastern Antioquia in Colombia has had success with incentive-based water pollution regulation. Water bodies in Colombia have been polluted heavily by untreated industrial and agricultural waste, contributing to a high incidence of water-related disease. To address this, Eastern Antioquia began to close factories and implement fines in 1995. However, many factories were able to find ways to avoid the regulations, and in 1997 this law was replaced with an incentive-based approach to meeting water quality standards by charging polluters per unit of biological oxygen demand and total suspended solids discharged. Pollution charges start low for each polluter, and ramp up every six months if pollution continues, creating an incentive to reduce discharges and purchase wastewater treatment technologies (Kraemer et al. 2001). One of the key components of its success is that charges are paid to local authorities, giving them both the incentive and resources to enforce the law.

In the first five years, organic waste was reduced by 27 percent, and suspended solids were reduced by 45 percent (Blackman 2006).

standards also need to develop funding streams, through public revenue, fines, and/or polluter-pays assessments to finance adequate enforcement.

Clearly, this discussion pre-supposes a functioning state that is not bankrupt and is able to enforce its own laws and to monitor accurately enough to determine when violations of water standards are taking place. Unfortunately, in many places, this is not the case. Thus, compliance is tied to capacity building within government and civil society. However, beyond direct enforcement there are a variety of other mechanisms that can provide incentives for compliance.

Market-based mechanisms

Market-based regulations can aid in the implementation of water quality regulations. These mechanisms encourage behavior, such as reducing pollution, through market signals, and are an alternative to the more traditional "command and control" mechanisms that typically hold all polluters to the same pollution control target. Because the cost of control measures can vary greatly among polluters, depending on the age and type of facility and other factors, holding all polluters to the same target can be economically inefficient (Stavins 1998). In contrast, market-based mechanisms are meant to achieve environmental goals at the lowest overall cost to society (Stavins 1998). Market-based mechanisms used to help achieve water quality goals include water pollution charges (or taxes) and water quality trading. However, despite having some benefits, market-based mechanisms also have serious drawbacks, particularly concerns about pollution being redistributed to poor neighborhoods.

Water-pollution charges require that polluters pay for their discharges, based on quantity and/or type of pollutants discharged (Kraemer et al. 2003). These charges motivate polluters to invest in treatment technologies or other pollution-reduction strategies to the extent that doing so costs less than paying the pollution charges. Because of the variability of control costs between facilities, some will achieve greater reductions than others. Of course, if the charge is not sufficiently high, there will be no incentive for polluters to reduce their discharges.

Water quality trading is another market-based mechanism which can maximize economic efficiency by allowing polluters with high abatement costs to pay polluters with lower abatement costs to reduce their discharges of specific pollutants. The right type of water quality regulation must be in place to motivate trading. A cap on the concentration of pollutants allowable in a water body must exist and this allowable pollution must be allocated among various sources of pollution.

Trading can occur between any combination of point and nonpoint sources of water pollution that are in the same watershed, for example between two agricultural producers, or an agricultural producer and a wastewater treatment plant. For example, in Cumberland, Wisconsin, farmers were paid to implement no-till farming or reduce the intensity of tillage on lands with high phosphorus content. This programme resulted in a reduction in phosphorus in the Red Cedar River and allowed the city to forgo expensive upgrades to their wastewater treatment facility (Market Watch 2002, CTIC 2006). In the Lake Taupo Trading Program in Waikato, New Zealand, allowable nitrogen runoff

Case study

Successful regulation of water quality for ecosystems through polluter-pays regulations in the Netherlands

During the 1960s in the Netherlands, water pollution loads, particularly organic pollutants, were becoming serious enough to interfere with the water's use for drinking water, recreation, and agriculture. In 1970, the Netherlands implemented the Pollution of Surface Waters Act, a pollution fine system that has been very successful in reducing water pollution. The system is based around the recognition that water needs to be clean enough not only for human uses (drinking water, agriculture, industry), but also for aquatic ecosystems (Van Erkelens and Olman 1996).

These regulations are at the national level, but water management is the responsibility of provincial governments. All of these 12 governments in the Netherlands have delegated water management responsibilities to Water Boards (Hank and Von Dokkum 2002).

Water quality regulations in the Netherlands rely on licensing and charging both direct and indirect sources of biochemical oxygen demand and heavy metals. Licenses are granted by Water Boards to companies and households that discharge effluents directly to waters. Fine levels are based on the goal of providing full cost recovery of sewage treatment (World Bank Group 1998). While the Netherlands is not the only country which has levied fines on polluters, their system has been particularly successful for a number of reasons. First, fines are based on volume of pollution discharged, incentivizing as little discharge of pollutants as possible (Elkins 1999). Fines are also substantial enough to discourage pollution, and have increased over time. There are also organizational reasons for success: polluters and the Water Board have direct interactions, and requirements are laid out clearly. Finally, revenue raised is used to finance wastewater treatment facilities, which further improve water quality (Van Erkelens and Olman 1996).

Dramatic water quality improvements were attained in nearly all regions of the country. For example, in the first 25 years of implementation, discharges of oxygen-binding substances dropped 80 percent (Van Erkelens and Olman 1996).

has been allocated on an acre-basis, and growers wishing to increase their nitrogen use need to purchase credits from other growers in the basin (Selman et al. 2009). Worldwide, 57 trading programs have been established in four countries (U.S., Canada, Australia, and New Zealand), with the vast majority in the U.S. (Selman et al. 2009).

However, there are also serious concerns with water quality trading programs. Pollution trading has been criticized by environmental justice groups for giving corporations the "right" to pollute, when this pollution is in conflict with the health of people and the environment (CEJM). Market-based redistribution of pollution has the potential to disproportionately impact disadvantaged communities. If the cost of pollution abatement is correlated with income or race, pollution trading will lead to increased concentrations of pollutants in poor and minority communities (NRDC 2003, Blacklocke 2005). Because of these equity concerns, pollution trading is generally not suitable for toxic contaminants. In any market-based water quality program, care needs to be taken to assess the potential impacts of pollution trading on human health and to avoid programs that will impact people negatively.

Consumer and investor pressure

Pressure from consumers and investors on the private sector can also provide powerful leverage in terms of changing water practices. This pressure often takes the form of consumer boycotts and media campaigns that publicize poor practices and call for fundamental change from within the company to address its shortcomings. For instance, media campaigns against the Coca-Cola Company have been launched by several international organizations and local consumer groups, including Corporate Accountability International, India Resource Center, and local community groups. These campaigns highlight poor water management: over-extraction of groundwater resources and inappropriate discharging of wastewater into local fields and rivers, along with high levels of pesticides and heavy metals in wastewater, have damaged the human and environmental communities around Coca-Cola production plants.

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In response, the Coca-Cola Company has committed to offset all water used for manufacturing to the environment, with the overarching goal of being "water neutral." The company pledged to set specific goals in 2008 for its global operations to reduce use of water and is striving to have 100 percent of facilities returning water used in manufacturing processes back to the environment at a level that will continue to support aquatic life by 2010. Lastly, Coca-Cola is working to replenish water through support of watersheds and community-level sustainability water programs. Although far from addressing the full set of poor practices identified by the media campaigns, particularly in relation to water quality, these actions clearly indicate a change in company policy in response to consumer and investor pressure that may improve water management practices.

Changing social norms

Social norms are spoken and unspoken rules that guide behavior, including values, beliefs, and attitudes. While they can be fairly specific to individual cultures, age groups, and social classes, they are very powerful in terms of impacting everyday choices. For example, the widespread adoption of water hygiene and sanitation was driven in large part by changing social norms. More recently, environmental movements combined with institutional changes from the international to the local scale have made materials recycling a common practice in many more affluent urban centers. Comprehensive container deposit regulations are in place in countries like Australia, Canada, Denmark, Germany, Norway, and Sweden.

In some of these countries, plastic bottle recycling rates can approach 90 percent. In Switzerland, there are bottle bins at every supermarket with separate slots for clear, green, and brown glass and for plastic bottles. As a result, 80 percent of plastic PET bottles are recycled there, far higher than the European average of 40 percent (Gleick 2010). Some countries are implementing "take-back" programs that require companies to either reduce waste volumes or accept packaging waste from their products for recycling or disposal.

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V. Conclusions and recommendations

The world is facing a rapidly increasing set of water quality challenges. Yet, effective solutions to these challenges exist and can be implemented. Solutions to water quality problems can be found at multiple scales. There is a great degree of variability in the water quality status and in the regulatory regime protecting water quality in countries throughout the world.

In regions that lack targeted national policies or adequate enforcement, sub-national or watershed-level protections may be effective. In places where municipal drinking water treatment and provision, sanitation, and sewage treatment do not exist or do not serve a significant portion of the community, neighborhood- or household-level solutions can be especially effective. And community pressure to improve water quality through regulation, enforcement, and incentives can be helpful at multiple scales.

At the household level, effective drinking water treatment can make a significant difference in improving the health of humans and ecosystems. The watershed level is important in water quality considerations because it links all of the different sources, users, and pollutants and considers the watershed as an important functioning unit. At a country level, national regulations, financing, and standardized monitoring can help move forward local reforms. At an international level, increasing attention to the issue, developing guidelines and standards, and promoting exchanges of lessons learned and success stories can be very effective at supporting local efforts.

Inequitable involvement of vulnerable men and women has hindered programs and projects aimed at addressing sustainability in water resource management. Power relations often place women in a disadvantaged position. Applying a comprehensive gender analysis spells great success in defining legislation, policies, and programs that will promote improvement of water quality and equitable distribution of water resources.

One of the principles of Integrated Water Resource Management states that women should be recognized as central to the provision, management, and safeguarding of water. Due to women's traditional roles in water resource management, they have valuable knowledge and skills that should be included in planning and practice.

Recommendations for moving forward to solve global water quality challenges encompass education and capacity building, legal, financial, technology and infrastructure, and data and monitoring. They are organized in the matrix (Table 8) and also detailed in the following section.

Recommendations

Education and capacity building

Water quality improvements can be achieved through the difficult work of changing social norms, advocating for improved policies, and demanding smarter investments. One of the most important strategies in the arsenal of the

Table 8. Matrix of solutions by scale

	Education & capacity-building	Legal	Financial	Technology/ infrastructure	Data/monitoring
International	Increasing global education and awareness building campaigns Promote gender equity in decision-making and participation	Promote model pollution prevention policies Create international guidelines on ecosystem water quality Create standards to characterize in-stream water quality and locate areas for remediation Strengthen transboundary governance frameworks for managing shared water resources Promote best practices and IWRM amongst river basin organizations	Developing more cost-benefit analyses of the benefits and costs of water quality Develop consumer and investor campaigns to exert pressure on the private sector to reduce water pollution Mobilize financing for proven, cost-effective water and wastewater treatment infrastructure, at multiple scales Mobilize financing for other recommendations Evaluation of ecosystem services and including them into the economic analysis	Ensure that international funding agencies finance infrastructure and water projects protect and/or improve water quality	Create international data protocols, standard data formats, and sharing arrangements Create standards and a recommended schedule for monitoring Increase the participation of developing countries and countries in economic transition in water quality monitoring, assessment and reporting Develop free access to satellite data suitable for monitoring inland and coastal water quality in developing and developed countries Monitor water quality over long-time scales and broad spatial scales
National	Develop water management capacity through formal education programs that focus on training future water experts, decision-makers, planners, and the public Conduct awareness building campaigns for the general public and policy-makers	Require policies that take integrated approaches to water management Regulate drinking water quality and quantity. Focus on pollution prevention Establish enforceable water quality standards that protect human and ecosystem health Change building codes and planning processes to consider non-structural water treatment options (e.g. Low Impact Development, source water protection) Promote comprehensive approach to water related legislation across different areas of law (waste management, chemical safety, etc) Promote access to information, public participation and access to justice in environmental matters.	Establish polluter-pays and beneficiary-pays principles Avoid inappropriate subsidies for water infrastructure of services Provide appropriate market incentives for efficient use and allocation, while protecting the interests of the poor and those without access to markets.	Provide financial assistance to communities in need of drinking water and sewerage infrastructure	Monitor key water quality and ecosystem indicators to track effectiveness of legal and other measures Evaluate water quality in concert with ecosystems in order to identify minimum ecosystem water needs Build national capacity to collect, manage and analyze water quality information Evaluate the links between water quality and water quantity Fund and publish research that addresses the time-series statistics needed to establish baselines, seasonality, and trends Improve monitoring technology, such as measuring water quality in real time and expanding the number and types of indicators that are monitored; and Promote low-cost, rapid, and reliable field sampling tools and technologies.
Watershed	Strategic level for raising awareness on the impacts of individuals on water quality	Create watershed-based planning units that integrate information, identify sources of pollution, and focus on reducing those source inputs Develop water quality goals and corresponding parameters for each water-body Promote access to information, public participation and access to justice in environmental matters.	User fees that recover full capital and O &M costs, and incentivize water efficiency Ensure that applied solutions provide ecosystem services for local societies	Invest in infrastructure and appropriate watershed management	Build regional capacity to collect, manage and analyze water quality information
Household/ community	Connect individual and community behavior to water quality impacts, and build capacity to make improvements in sanitation/wastewater and drinking water treatment	Amend city and community codes to allow innovative stormwater treatment options Promote access to information, public participation and access to justice in environmental matters.	Investments	Consider decentralized treatment technologies	Review data provided Contribute to solutions

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water quality advocate is the tool of building social change through education and capacity building.

Particularly in an unregulated environment, it is easy to throw things into the water, like industrial byproducts, agricultural waste, or human waste. Regulations and enforcement can help change behavior and lead to new technologies and financial investments to improve water quality. But all of these strategies can only be implemented once a society decides that water quality is a problem. To have societies make improving water quality a priority, they need to have knowledge about its connections to the things they care about.

Demonstrating the importance of water quality to residents, the media, policy makers, business owners, and farmers can have a tremendous impact in winning key improvements. A first step in this is to connect the abstract concept of water quality to the key roles that water plays culturally, socially, historically, and in ecosystem and human health.

Once people are convinced about the importance of water quality, they then need to be able to assess the current quality of waterways and have the tools and capacity to implement change, so the next stage in an education campaign should be a water quality assessment. With information on the importance of clean water for life and health, and research on the current state of the waterways in hand, communities need ways to translate this knowledge into water quality improvements. This requires tools to engage other community members, activate the media, develop solutions, and advocate with policy makers. This capacity building is an important part of education so that positive results can flow from increased knowledge.

Capacity building and education efforts are needed at every scale. At the household and community scale, these efforts are important because they can improve individual behavior and join individuals together as a community voice to demand better regulations and enforcement. Education and capacity building at larger scales can promote effective watershed, national, and international interventions that develop better standards, regulation, and enforcement to improve collective behavior. Including water education in the formal educational curricula is a key intervention to step up to higher scales of awareness.

Legal

In the coming decade, water resources will be under increasing stress from persistent and emerging challenges including population growth, urbanization, new contaminants, and climate change. The Economic Commission for Europe recently concluded that:

> "Strengthening institutions for land and water management is crucial to effective adaptation and must build on principles of participation of civil society, gender equality, subsidiarity and decentralization… Social and institutional innovation is a key aspect of an efficient adaptation framework. This may imply revising governing arrangements, decision-making mechanisms, budgetary processes, etc." (Dialogue on Land and Water Management for Adaptation to Climate Change).

Similarly, legal and institutional frameworks for water quality protection must evolve from fractured, and often unenforceable, guidelines to a comprehensive approach to pollution prevention and source water protection along with other "no-regret" options that reduce water pollution, energy use, and environmental risks at once. Recommendations offered here range from broad actions at the international level to specific actions at the watershed and community level. At the international scale, model pollution-prevention policies should be developed and disseminated. In addition, guidelines should be developed for ecosystem water quality (as they are for drinking water quality). At the national scale, new institutions and regulatory actions are needed to take an integrated approach to water that prioritizes pollution prevention and sets enforceable water quality standards. The watershed scale is also an important planning level, in terms of identifying major sources of pollution and appropriate interventions. Many countries are already beginning to create management institutions at the watershed scale, which are important in order to implement broad national or international directives on the ground.

Recommendations include:

- create international guidelines on ecosystem water quality;
- create standards to characterize in-stream water quality and locate areas for remediation;
- promote model pollution-prevention policies;
- require policies that take integrated approaches to water management;
- regulate drinking water quality and quantity;
- establish enforceable water quality standards that protect human and ecosystem health;
- change building codes and planning processes to consider nonstructural water treatment options (e.g. Low Impact Development, source water protection);
- create watershed-based planning units that integrate information, identify sources of pollution, and focus on reducing those source inputs;
- develop water quality goals and corresponding parameters for each water-body;
- amend city and community codes to allow innovative stormwater treatment options.

Financial

Finding appropriate sources of financing, and defining appropriate methods for evaluating costs and benefits of improving water quality, are both critical challenges. Until recently, national and international financial agreements for water and wastewater treatment infrastructure often failed to acknowledge the value and importance of maintaining ecosystem services and the role of water systems in water purification. Historically, many projects degraded ecosystem services and functions, causing unanticipated costs that exceeded the value of the project itself. Integrated water resources management seeks to balance ecosystem and human needs. National and international funding for water quality improvements should follow the principles of integrated water resources management, assessing problems and potentials on a watershed scale and ensuring that new projects do not exacerbate or create new ecological impacts. In many cases, it will be appropriate for some portion of grants or loans to be dedicated toward protection and restoration of freshwater ecosystems to enhance ecosystem services and avoid unwanted costs.

In order to ensure that society appropriately values the services that water quality and ecosystems provide, more cost-benefit analyses for water quality need to be developed. Investor or consumer pressure can also help businesses and corporations appropriately value water quality as an output. Water charges also need to be appropriate so that they provide incentives for water efficiency, which also reduces the quantity of water that is being contaminated by pollutants. Inappropriate subsidies for water infrastructure and services that do not improve or protect water quality should be avoided. User fees are needed for water and wastewater services that fully recover capital and operations costs and also allow utilities to invest in protecting water quality and protecting source water. Polluter-pays principles need to be implemented so that activities that release pollution into waterways internalize the costs of pollution instead of socializing the costs and impacts.

Technology/infrastructure

Many effective technologies and approaches are available to improve water quality. Appropriate technologies can be used to treat wastewater if funding is available to communities to implement needed technology and infrastructure. A tremendously cost-effective approach to improving water quality is through pollution prevention. In cases where contaminants result from domestic, industrial, or agricultural activities, wastewater must be treated. When water quality and watersheds are adversely impacted by poor water quality, strategies to remediate pollution and restore watershed functions are important.

Technologies and infrastructure to prevent, treat, and restore water quality must be employed in every region of the world by:

- connecting communities, governments, and businesses to effective water quality technologies and approaches;
- developing new technologies when needed to meet the particular environmental or resource conditions in a particular location;
- providing financing to implement needed technologies and infrastructure projects;

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- providing technical and logistical support to help communities and governments implement technology and infrastructure projects to improve water quality.

Data/monitoring

Good data and ongoing monitoring are the cornerstones of an effective effort to improve water quality. In order to protect and improve water quality, water managers, governments, and communities need to know what pollutants are in the water, how they entered the waterway, and if efforts to improve water quality have been effective. Plans to improve water quality cannot be implemented without clear understanding of what contaminants are in the water and how they are affecting the ecosystem and human health. Addressing water quality challenges will mean tracing water contaminants to their source and identifying a prevention and/or treatment plan. Once the treatment plan is implemented, ongoing monitoring of water quality will help us ascertain whether the remediation efforts have been successful. Based on this information, the treatment can be continued or modified to include additional sources and pollutants until desired levels are reached.

Monitoring efforts worldwide need to be improved. In order to increase comparability of data worldwide, international data protocols, standard data formats, and sharing arrangements are needed. Similar to what has been done in other sectors, international guidelines need to be developed on how often and for what pollutants waterways should be monitored. Expanding the time scales and geographic scales over which water quality is monitored will improve management decisions. In order to identify hotspots and needed areas of intervention, national capacity needs to be developed in all countries to collect, manage, and analyze water quality information. Where these resources are missing, they should be provided through international aid or other mechanisms.

As developing countries undergo economic transitions, water quality monitoring and reporting need to be integrated into new laws. As satellite data to monitor water quality become more readily available, resources should be made available to help developing countries access, analyze, and use these data. Funding and publishing more research that provides time-series statistics is needed to establish baselines, seasonality, and trends. In order to preserve the role water quality plays in ecosystems, efforts to jointly monitor key water quality and ecosystem indicators must be implemented to track the effectiveness of legal and other measures, improve data sharing, and better coordinate water quality protection efforts.

There is also a need for better and cheaper ways of quickly and accurately measuring water quality. Monitoring technology needs to be improved also so that water quality can be measured in real time and the number and types of indicators that are monitored can be expanded with low-cost, rapid, and reliable field sampling tools and technologies.

Moving forward

For many centuries, humans have been living on the banks of rivers, overlooking streams, and on coasts, relying on nature to provide clean water and remove wastes. As populations grew, these water resources became increasingly contaminated, leading to growing epidemics of water-related diseases. Ultimately, improvements in knowledge, technology, and water management gave birth to a new way of interacting with water. As impacts of poor water quality on human health were identified, technologies and strategies were developed to reclaim the multiple roles that water played in human society.

Today, water is still used to satiate thirst, power industries, grow food, and take away waste. More rapid population growth, industrialization, and urbanization introduce a whole new set of water quality challenges. These expanded water quality threats can in part be addressed using the same concepts that led the public health revolution in the mid-1900s. But new approaches are needed as well, such as the responsibility to meet human needs while protecting both


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human and environmental health, the acknowledgement of the importance of preventing pollution before it enters waterways, and the idea that water must be managed at watershed, not narrow political, boundaries – these concepts can play an essential role in tackling future threats to water quality.

While watersheds have amazing powers to restore their health, the natural processes that can help remediate and restore the functioning of watersheds need to be promoted and protected. Ecosystems play an important role in preventing pollution, and treating and restoring the quality of water. Efforts to protect water quality and to include all actors who interact with watersheds need to be expanded to every corner of the globe. To support this paradigm shift to protect and improve water quality, education and capacity building are critical tools. Education and public pressure were crucial in the first global wave to protect water quality, and will be invaluable in this new era. Regulatory and legal tools, as well as appropriate financial and economic tools necessary to support, maintain, and enforce water quality are a priority. Technology and infrastructure can help achieve water quality goals, and data and monitoring will help gauge progress toward achieving water quality goals.

The decisions made in the next decade will determine the path we take in addressing the global water quality challenge. Disturbing scenarios of the future are certainly possible: if we fail to address water pollution now, more waterways in developing country cities will become no more than open running sewers, with buildings and houses turned away from the waterways to keep away from the brackish and stagnant water and the stench. More industrial waste and sewage means fewer people will be able to go to a nearby stream to catch fish for dinner or for livelihood. More people will die from preventable waterborne diseases if the problem of safe sanitation and clean drinking water remains unsolved. Industries and farms will spend more and more money to find and treat water that is clean enough to use.

Taking bold steps internationally, nationally, and locally to protect water quality will mean a much different future. Waterways can again become the centerpieces of cities and villages, the cultural and social gathering places, and residents will once again turn toward the rivers and streams that gave them life. The choicest property will be overlooking the vibrant waterways that flow through human settlements. And in places throughout the world, the lost art of swimming in local rivers and lakes and fishing for recreation and sustenance will thrive again. Pollution prevention efforts will save industries and farms money, which they re-invest in restoring the waterways that provide them with much needed clean source water. Instead of spending more money and energy on water treatment, utilities and communities will be able to focus on protecting the sources of drinking water.

Watersheds become a new hallmark of this positive future, where the smallest child will know from where the water she is about to drink has come. And she and her family and community will be committed to ensuring that every drop that enters the watershed is clean, from the water that percolates into the ground through low impact development efforts, to the cleaned-up effluent from manufacturing processes, to the clean runoff from farms, to the most effective wastewater treatment. In this future, everyone has safe water to drink, everyone has a place to swim and fish, and everyone has a place to enjoy the natural beauty of rivers and lakes – and everything is possible.

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ACRONYMS

ATSDR	Agency for Toxic Substances and Disease Registry
BOD	Biological Oxygen Demand
CEJM	California Environmental Justice Movement
CDC	Centers for Disease Control
COD	Chemical Oxygen Demand
CPT	Cleaner Production Technology
CLEAN-India	Community Led Environmental Action Network-India
CLTS	Community Led Total Sanitation Movement
CTIC	Conservation Technology Information Center
DANIDA	Danish National Aid Agency
DRP	Danube Regional Project
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DALY	Disability adjusted life years
DTIE	Division of Technology, Industry and Economics
EO	Earth Observation
EAT	Environmental Affairs and Tourism (Republic of South Africa)
ENHIS	European Environment and Health Information System
EU	European Union
WFD	European Union's Water Framework Directive
FISCRWG	Federal Interagency Stream Corridor Restoration Working Group (U.S.)
FAO	Food and Agriculture Organization of the United Nations
GWA	Gender and Water Alliance
GEF	Global Environment Facility
GEMS	Global Environment Monitoring System
GIWA	Global International Waters Assessment
GWP	Global Water Partnership
GWP-TAC	Global Water Partnership - Technical Advisory Committee
GDP	Gross domestic product
GEO	Group on Earth Observations
IEDS	Institute for Environment and Development Studies
ILBM	Integrated Lake Basin Management Approach
IWRM	Integrated Water Resources Management
IANWGE	Interagency Network on Women and Gender Equality
IPCC	Intergovernmental Panel on Climate Change
IARC	International Agency for Research on Cancer
IETC	International Environmental Technology Centre
IFAP	International Federation of Agricultural Producers
IFC	International Finance Corporation
IGRAC	International Groundwater Resources Assessment Centre
ILEC	International Lake Environment Committee Foundation
ILA	International Law Association
ISO	International Organization for Standardization
IUCN	International Union for the Conservation of Nature
IRC	International Water and Sanitation Centre
IW LEARN	International Waters Learning Exchange and Resource Network
LVEM	Lake Victoria Environmental Management
LID	Low Impact Development
MIT	Massacusetts Institute of Technology
MSF	Médecins sans Frontières
MENA	Middle East and North Africa
MDG	Millennium Development Goals
MA	Millennium Ecosystem Assessment
NCPC	National Cleaner Production Centres
NHD	National Hydrography Dataset (U.S.)
UNAG	National Union of Farmers and Ranchers (Unión Nacional de Agricultores y Ganaderos)
NWIS	National Water Information System (of the U.S. Geological Survey)
NAWQA	National Water Quality Assessment (U.S.)
NRDC	Natural Resource Defense Council
NGO	Non-governmental organization
O&M	Operations and maintenance

OSU	Oregon State University
OECD	Organisation for Economic Co-operation and Development
ODI	Overseas Development Institute
POPs	Persistent organic pollutants
PAN	Pesticide Action Network
PANNA	Pesticide Action Network North America
PV	Photovoltaic
PCB	Polychlorinated biphenyls
PET	Polyethylene terephthalate
REACH	Registration, Evaluation and Authorization of Chemicals
RO	Reverse Osmosis
SIRDC	Scientific and Industrial Research and Development Centre
SER	Society for Ecological Restoration
SA DWAF	South African Department of Water Affairs and Forestry
SEI	Stockholm Environment Institute
SIWI	Stockholm International Water Institute
STORET	Storage and Retrieval data warehouse (U.S.)
SIDA	Swedish International Development Cooperation Agency
PCaC	The Campesino to Campesino Program (Programa Campesino a Campesino)
ES	The Endocrine Society
WB	The World Bank
TEST	Transfer of Environmentally Sound Technologies
UN	United Nations
UNICEF	United Nations Children's Fund
UN-DESA	United Nations Department of Economic and Social Affairs
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environment Programme
UNEP-ROA	United Nations Environment Programme-Regional Office for Africa
UNIDO	United Nations Industrial Development Organization
UNWTO	United Nations World Tourism Organization
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
GAO	United States Government Accountability Office
US NAS	United States National Academy of Sciences
WGF	Water Governance Facility
WRIP	Water Reuse Implementation Project
WSSCC	Water Supply and Sanitation Collaborative Council
WASH	Water, sanitation and hygiene
WATERS	Watershed Assessment, Tracking, and Environmental Results (of the United State Environmental Protection Agency)
WHO	World Health Organization
WHO-SEA	World Health Organization South East Asian region
WLVARC	World Lake Vision Action Report Committee
WMO	World Meteorological Organization
WWAP	World Water Assessment Programme

www.unep.org
United Nations Environment Programme
P.O. Box 30552 Nairobi, Kenya
Tel: (254 20) 7621234
Fax: (254 20) 7623927
Email: uneppub@unep.org
web: www.unep.org

UNEP

United Nations Environment Programme (UNEP)
Division of Environmental Policy Implementation
P.O. Box 30552
00100 Nairobi, Kenya
Tel.: +254 20 762 3753
Fax: +254 20 762 4249
e-mail: depi@unep.org

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