6

WATER RESOURCE QUALITY *

Contents

* This chapter was prepared by Scott Fulton.

"Water quality" is a concept grounded in relativity: the desired quality of a given water resource relates to the use desired of that resource. For example, a water resource that is intended for use as drinking water must be relatively pollution-free so that it is suitable for human consumption, whereas water that is intended for recreational purposes can be less pristine and still serve its intended purpose. Thus for water quality the key question is, "how clean is clean?"

An integral part of maintaining water quality is pollution control. Pollution can reduce the quality of water to the point of rendering it unsuitable for any meaningful human use and destructive to broader and dependent ecosystems. Pollution control is therefore fundamental to the use, protection and preservation of water resources.

This chapter considers the challenge of maintaining water quality through pollution control or, in the case of already polluted waters, recovering water quality. It begins by reviewing the complexity of freshwater systems and the nature and sources of water pollution. It describes the effects of pollution on humans, animals and ecosystems. The chapter then looks more closely at two principal categories of water pollution – "point source" pollution (pollution conveyed to water systems by discrete sources) and "non-point source" pollution (pollution without a discrete source), and suggests actions and policies that can help prevent and alleviate both kinds.

Although water pollution control can be a technical subject, this chapter does not attempt to catalogue the various means and methodologies for its mitigation. Rather, it considers the social, economic and health factors relating to water pollution, the principles that tend to inform government responses to it and the tools and strategies typically deployed in water pollution control.

I. WATER QUALITY

1.1. The water cycle and water quality

As described in Chapter 2, our world's water systems are best understood not as a series of discrete and separable water bodies but rather as a complex and inter-related network within which many natural cycles and processes are constantly at work. For example, through the cycle of evaporation and precipitation, water molecules from surface moisture become airborne and then return to the earth as rain and snow, feeding the streams, tributaries, rivers, lakes and oceans that provided the bulk of the evaporate in the first place. Groundwater bodies are commonly inter-connected and generally both discharge to and are recharged by surface waters. These are all features of the water cycle (UNEP, 2005).

Pollution introduced anywhere in this cycle is ordinarily unconfined and amenable to distribution. Thus, when water molecules bind with air contaminants in the atmosphere, the result is precipitation that brings a pollution load back to the surface waters that it replenishes. A contaminated stream not only conveys pollution to other downstream surface water bodies but can also provide a polluted recharge to an underground aquifer. And polluted groundwater not only presents a risk of pollution migration to other parts of the underground system but can also carry pollution to the surface water bodies to which it discharges. A meaningful approach to ensuring water quality, therefore, must appreciate these synergies.

After the eventual recognition of the human and environmental implications of water pollution over the last century, considerable progress has been made in understanding how fresh water systems function and in developing control strategies for protecting them. Yet, success in deploying these strategies has been uneven at best. Water quality all too often turns on the sufficiency of the resources needed to develop and implement the necessary protections and on the political will needed to transform an emerging concern into a societal priority. Fortunately, there is today a substantial body of collective experience that nations may draw upon in designing water pollution control systems, which should ease the resource burden. With increased understanding of the true cost of degradation of fresh water resources, water pollution is no longer seen as an insignificant second-tier political concern. Rather, it is appropriately understood as integral to a nation's long-term sustainability and survival.

1.2. The surface water/groundwater interface and water quality

Groundwater serves as a major source of the world's drinking water. Identifiable and reasonably well-defined groundwater bodies are known as aquifers, which are typically porous geologic formations – composed of such materials as sand, gravel or limestone – which contain water. An aquifer is ordinarily not a confined system, but rather is subject to various externalities, such as recharge from surface water bodies (which are often more contaminated); migration of water from other polluted groundwater systems; and "leaching" of contaminants and wastes from ground surfaces down through the soil and into the aquifer (UNEP, 2005).

Accordingly, although the quality of groundwater is frequently better than that of surface water, its quality is highly sensitive to activities that take place on the surface. For example, as a result of manufacturing and agricultural activities, groundwater resources often become contaminated with heavy metals, nutrients and chemical compounds used in fertilizers or pesticides. The management of wastes – both ordinary municipal solid waste and hazardous waste – is also of great importance to the preservation of groundwater quality. For example, it is a common waste management practice to dispose of such waste simply by burying it. The assumption is, "out of sight, out of mind." But when solid and hazardous wastes are buried without proper attention to such protective devices as landfill liners, leachate collection systems and groundwater monitoring wells, groundwater resources can be put at serious risk of contamination.

Once an aquifer has become contaminated, restoring it often requires a complex process of removing the surface or sub-surface source of the pollution, pumping the groundwater to the surface where it can be treated and then recharging the aquifer with treated, clean water. This kind of "pump and treat" remedy can take years to execute and can be quite costly, making prevention of groundwater pollution in the first instance an acute priority.

1.3. Watershed management and water quality

The term "watershed" describes the total land area from which water drains into a particular stream or river. Watersheds can be large or small. Every stream, tributary or river has an associated watershed, and small watersheds are often parts of larger ones.

Inherent in the watershed concept is the idea of "connectivity" – the physical connection between tributaries and rivers, between surface water and groundwater and between wetlands and both surface water and groundwater. Water moves downstream and therefore any activity that affects water quality at one location affects locations downstream as well. For this reason, a serious approach to ensuring water quality requires consideration not only of water quality at a particular location of concern, but also upstream problems that may have downstream impacts.

This will require special attention where water bodies or watersheds are not contained within national borders. Arrangements typically play out according to principles of international law and international agreements among the involved states. According to the principle of equitable use, states are free to exploit resources within their territories, but must do so in a way that does not impair the resource rights of other states. In the pollution control context, this would mean that upstream states have a responsibility to downstream states to avoid degradation of shared water resources. Equally, the principle of cooperation holds that states should work in a consultative and collaborative manner to reduce and control the pollution of shared watercourses by, amongst other things, establishing common water quality objectives and harmonizing national laws and policies relating to such watercourses.

II. WATER POLLUTION

2.1. Defining "pollution" in the water context

The common understanding of the term "pollution" is the introduction into the environment, directly or indirectly, of substances that change environmental conditions and result in harmful effects, either because of their nature or quantity. Another definition refers to the impairment of the designated use of a water body or resource caused by changes in water characteristics.

Not all pollution is anthropogenic (i.e. generated by human activity); some of it occurs naturally as a result of natural formations and events that release substances that affect water quality. For example, naturally occurring pollution can come from fires, volcanic eruptions or the drowning of large animals. Some groundwater is contaminated by naturally occurring pollutants such as arsenic or salt. Such natural pollution cannot be regulated, although governments have often attempted to develop response mechanisms to limit its impact.

Anthropogenic pollution is the most important concern from a water management standpoint because it is both subject to control and a major source of water quality problems. Not all anthropogenic pollution is harmful, however. The environment has the capacity to assimilate pollution up to certain limits, and it is only when these limits are exceeded that pollution is cause for concern. Put another way, the presence of a pollutant in a water body does not necessarily mean that the water body is polluted. It depends on both the concentration of the pollutant and the intended water use.

Anthropogenic pollutants generally fall into two categories. "Stock pollutants" are pollutants that accumulate with little or very slow degradation because the capacity of the environment to assimilate them is very small (i.e. they persist in the environment) and "fund pollutants" are pollutants that, by contrast, decompose and thus do not as readily tax the assimilative capacity of the receiving stream. An example of stock pollutants would be inorganic chemicals and heavy metals that cannot be removed by natural processes, whilst an example of "fund pollutants" would be human and animal wastes. Management of stock pollutants is typically preventative, in the sense that the introduction of such substances into the environment should be avoided or reduced. Management of fund pollutants often focuses both on prevention and on creating conditions that enhance degradation or allow natural degradation to convert the pollutants into an innocuous form.

2.2. Types of water pollution

Anthropogenic water pollution can be grouped into three general pollution categories: physical, organic and toxic. Each of these is discussed below and also set out in Box 6.1.

Physical. Physical pollution consists of pollution that materially changes the physical characteristics of a water body. Some pollutants dissolve in water whilst others, composed of larger particles, remain suspended in the water. Eventually, these particles settle and form silt or mud on the beds of water bodies, decreasing the depth of the water body and affecting aquatic life. This sedimentation is one example of physical pollution. Another form of physical pollution is the discharge of objects and solid wastes (e.g. plastic, paper) into water bodies. Such pollution impairs the landscape, obstructs waterways and can be harmful to wildlife.

Another type of physical pollution is thermal (hot water) pollution. Thermal pollution occurs when water used for cooling in power or industrial plants is discharged heated into a water body. Conversely, when water is taken from a water body – for example, diversions from a river for use in irrigated agriculture – the remaining water body will have a smaller volume and will therefore heat more rapidly (depending on solar radiation and ambient temperature). Thermal pollution increases the temperature of water and can lead to both a decrease in the dissolved oxygen level in the water and an increase in the biological demand of aquatic organisms for oxygen. The results are commonly a reduction in the number of organisms that can live in the water body and disruption of the water body's ecological balance, because some plants and animals are killed whilst others' growth is stimulated.

Similarly, cold water pollution can seriously affect the water environment. Releases of cold water occur downstream from dams (because water is discharged from the bottom of the reservoir rather than the surface) and can have the following negative consequences: elimination of native fish; loss of recreational uses; and proliferation of non-indigenous cold water fish, resulting in additional pressure on native species from predation and competition for food sources and habitat.

Box 6.1 - Types of Pollutants and Their Origins

Type	*Origin*
Physical	land surface erosion litter and mismanaged solid waste organic matter runoff from buildings or construction sites diversion of flow from rivers storage of water behind dams
Organic	organic matter fertilizers sewer overflow detergents animal and human wastes
Toxic	pesticides herbicides runoff from buildings and roads (oil) detergents

Organic. Organic pollution consists of organic wastes and compounds. As noted above, depending on the nature of the organic pollutant, freshwater bodies can often assimilate a certain amount of organic pollutants without serious effects. However, left unabated, organic pollution can alter the ecological balance of the water body. Organic pollution most frequently comes from human or livestock wastes and agricultural fertilizers. Mild organic pollution usually reduces biodiversity by increasing the populations of organisms that feed directly on organic materials. Organic pollution can also cause blooms of algae. The abundance of organic material can also affect the bacteriological population, in that bacteria that were previously limited in number due to a lack of food undergo a population explosion. These bacteria can reduce the amount of available oxygen, particularly in slow-moving water. If severe enough, the lack of oxygen (a condition known as hypoxia) can kill fish and other aquatic life.

Toxic. Toxic pollutants are those compounds and contaminants (such as some chemicals, solvents, acids, alkalis, heavy metals, pesticides and oil) that are poisonous to humans, animals or the environment. They cause toxicity, which occurs when a living organism experiences detrimental effects upon exposure to a substance. If toxicity is acute, short-term exposure produces the detrimental effect; if toxicity is chronic, the detrimental effects arise only after prolonged or continued exposure. If chronic toxicity leads to abnormal cell growth, the substance is known as a "mutagen" and may even cause cancer. In terms of human health, chronic toxicity may cause rashes and irritations, cancer and a reduction in reproductive capacity amongst individuals who are exposed to toxic water pollution.

Although all toxic pollution is cause for concern, two classes of toxic pollutants bear particular note: persistent organic pollutants (POPs) and heavy metals. POPs are toxic substances composed of organic (carbon-based) chemical compounds and mixtures that persist in the environment and pose a risk of adversely affecting human health and the environment. Through "bioaccumulation" or "biological magnification", their concentration increases at higher levels in the food chain and thus they can be very harmful to human health.

Heavy metals naturally occur in soil and water, but their worldwide production and use by industry, agriculture and mining have released large additional amounts into the environment. Water pollution related to metal production and use, including the release of acids from mining wastes, is a problem in many of the world's mining and metal processing regions. Elevated levels of some metals, such as lead and mercury, are also found around many cities, particularly if they are downstream or downwind from metal smelters and coal-burning power plants (UNDP, 1999). Some of the metals of greatest concern for human health are lead, mercury, arsenic and cadmium. Many other metals – including copper, silver, selenium, zinc and chromium – are highly toxic to aquatic life.

2.3. Sources of water pollution

Sources of water pollution generally divide into two classes: point sources and non-point sources. Point source pollution is pollution that comes from discrete and identifiable points (or outfalls) that discharge directly into a hydrologic system. Such discharge points are usually associated with industrial activities and municipal sewerage plants. The presence of pollutants in point source wastewater harms the quality of the receiving water body and limits the possible uses of that resource.

Non-point source pollution is pollution delivered to water systems through runoff, infiltration and other unchanneled means. It often derives from multiple sources or from sources that are not readily identifiable and enters the freshwater system as a result of natural processes such as rainfall or melting snow. Runoff from all kinds of surfaces – including industrial sites, agricultural areas and municipal areas – carries various pollutants into water bodies. Pollution can also be delivered by rain or snow that has bound with pollutants in the atmosphere.

Three anthropogenic activities – industry, agriculture and urban settlement – are common sources of point source and non-point source water pollution and are described in detail below.

2.3.1. Industry

Primary and secondary industrial activities – the extraction of raw materials and their processing – are responsible for the emission of numerous kinds of pollutants, including grit, phosphates, nitrates, mercury, lead, caustic soda and other sodium compounds, sulphur and sulphuric acid, oils and petrochemicals. In addition, many manufacturing plants discharge undiluted corrosives, toxins and other noxious by-products. The construction industry discharges slurries of gypsum, cement, abrasives, metals and hazardous solvents. Another pervasive group of contaminants used and discharged by industry is synthetic chemicals, such as polychlorinated biphenyl (PCB) compounds and components of lubricants, plastic wrappers and adhesives.

Mining consumes, diverts and can seriously pollute water resources. The impact of mining on water resources depends on a variety of factors, such as the composition of the minerals being mined, the type of technology employed and the skill, knowledge and environmental commitment of the mining company in question. Mining produces a large amount of different wastes, all of which need to be managed properly. Waste rocks and mine tailings, for example, often contain acid-generating sulphides, heavy metals and other contaminants, and are often stored in free-draining areas or in containment areas that are not well monitored or controlled (classic non-point sources). These areas can be a source of pollution for surrounding water resources, as they can leach through the soil or be washed away by runoff.

In the manufacturing sector, wastewater typically requires treatment before it can be discharged into freshwater systems. Such treatment must be carried out using appropriate technologies and in compliance with government directives and regulations. Industrial plants often have their own treatment facilities. They also frequently rely on publicly owned treatment works (POTWs) for the treatment of their wastewater, discharging to water resources via a so-called "indirect discharge". The major risk of indirect discharge is that receiving POTWs may not be equipped to deal with specific pollutants suspended or dissolved in industrial wastewaters. These may simply pass through the POTW or upset the system's ability to treat other waste. The net result is polluted water discharged by the POTW.

Industrial activities also release gases and airborne particulate matter that can result in air pollution. As noted, this atmospheric pollution may eventually pollute water resources through deposition or precipitation. Industrial activities may also cause thermal pollution, since industrial processes need effective systems for chilling machinery during and after use, and water is commonly used for this purpose.

Finally, runoff from industrial areas can carry pollutants into the freshwater system. The storage and disposal of hazardous waste generated by industrial processes is one common source of such pollution. Failure to handle and store such waste properly can result in dangerous discharges reaching freshwater systems through storm sewers and floor drains and through other direct and untreated discharges. Cleaning materials used in industrial operations also often contain harmful constituents and can themselves present problems when washed into water bodies.

2.3.2. Agriculture

The greatest demands placed on the world's water resources come from agriculture, which is also a major cause of water pollution. Agricultural pollution is most commonly a non-point source, in that it often runs off from large areas of land rather than being channelled through discrete conveyances. However, agricultural operations sometimes include identifiable point source discharges, particularly in concentrated livestock operations.

The main water quality problems associated with agriculture are salinization, nitrate and pesticide contamination and erosion that causes an increase in suspended solids in rivers and streams and siltation. Pollutants originating from agricultural activities include nutrients, heavy metals, pesticides, sediments, oxygen demand substances and pathogens.

The use of fertilizers (often composed of phosphorus, nitrogen and potassium, manure, sludge, irrigation water or crop residues) to enhance production can contribute negatively to water quality. When applied in excess of plant needs, such nutrients can wash into aquatic systems where they may cause excessive plant growth that can kill fish and other wildlife, create a foul taste and odour in drinking water and reduce recreational opportunities (Verona *et al.*, 2000). The same is true of pesticides, herbicides and fungicides, which can enter and contaminate water through direct application, runoff, wind transport and atmospheric deposition. Because they are specifically designed to kill living organisms, these chemicals are equally lethal to non-target fish and wildlife, poisoning food sources and destroying animal habitats.

Although irrigated agriculture is an essential component of any strategy to increase global food supply, irrigation itself can present a number of challenges to water quality. Problems such as waterlogging, salinization and erosion can damage irrigated areas, rendering them unsuitable for productive agricultural use and creating water quality concerns for surrounding water bodies. In particular, if improperly managed, irrigation can contribute to erosion and siltation and cause downstream degradation of water quality due to the effects of salts, agrochemicals and harmful leachates. Irrigation return flows, which collect runoff from cultivated areas, can carry high concentrations of pesticides, herbicides and nutrients to nearby waters.

Inefficient irrigation can pose other water quality problems. In arid areas, for example, where rainwater does not carry residues deep into the soil, excessive irrigation can concentrate pesticides, nutrients, disease-carrying micro-organisms and salts in the top layer of soil, where they pose a greater risk of reaching water systems via erosion and runoff.

The accumulation of pesticides and agricultural fertilizers in local watersheds has serious health consequences for farming families, including high rates of cancer and foetal malignancies or miscarriages. It can also kill wildlife and disrupt the ability of animals living in the watershed area to reproduce. The employment of wastewater for irrigation purposes, although an important strategy in water-scarce regions, can also increase the amount of contaminants that reach water resources when the wastewater is not adequately treated prior to use. The human health effects of these and other types of pollution are discussed at greater length in the next section and in Chapter 8.

Animal farming also presents serious water quality challenges. Animal husbandry generally requires pastureland, feed lots and facilities for keeping animals, and commonly generates significant amounts of organic waste which can pollute both surface water and groundwater resources. Although confining large numbers of animals to areas or lots allows farmers and ranchers to efficiently feed and maintain livestock, these areas often become concentrated sources of animal waste. Runoff from poorly managed facilities can carry pathogens (bacteria, viruses, parasites), nutrients and oxygen-demanding substances that can contaminate fishing areas and pose other water quality problems. Groundwater can also be contaminated by seepage from such facilities.

Silviculture and other forest management activities also present water quality concerns. Since forests stabilize local soils and hydrology, forest management – i.e. the felling or clearing of trees and brush in woods and forests to allow for agricultural activities and the harvesting of trees for wood products – can contribute significantly to soil erosion, increase siltation in local water resources and generally affect the quality of surface water runoff.

Aquaculture is also a significant source of water pollution. Waste from fish farming, including fish faeces and unconsumed feed, can contain excess amounts of nitrogen, phosphorus, ammonia, bacteria and industrial chemicals.

2.3.3. Urban areas

Urban areas have profound implications for watershed management and often significantly pollute water resources. Urban structures frequently interfere with natural hydrologic processes by creating barriers to groundwater movement and affecting groundwater recharge. Non-industrial urban water pollution takes two main forms – discharges from municipal sewerage systems and runoff from urban surfaces – but solid waste disposal and transportation are other important urban sources of water pollution.

Modern cities typically have systems for collecting and channelling wastewater from private dwellings, businesses and public buildings. To be environmentally safe, this municipal wastewater must be treated before being discharged into freshwater systems. There are three general classes of treatment for municipal wastewater: primary treatment, which typically includes grit removal, screening, grinding and sedimentation; secondary treatment, which ordinarily entails oxidation of dissolved organic matter by means of using biologically active sludge that is then filtered off; and tertiary treatment, which employs advanced biological methods for nitrogen removal and various advanced chemical and physical methods such as granular filtration and activated carbon absorption.

The existence and enforcement of regulations governing wastewater discharge are an important factor in determining the extent of treatment in a given urban environment. The financial health of the local government and the availability of financial assistance such as grants or bonds for the construction and maintenance of treatment facilities also play an important role in how extensively urban wastewater is treated.

Even reasonably well-developed and maintained treatment systems can contribute to pollution problems in freshwater systems. For example, detergents and cleaners used in private dwellings, businesses and public offices often contain phosphorus compounds that are not fully removed by treatment systems. These phosphorus compounds act as nutrients when they reach water bodies. Further, industrial wastewater conveyed to municipal treatment facilities (indirect discharges) may contain constituents that fall outside the treatment efficacy of a given plant and thus pass through the facility untreated, potentially interfering with the biological processes upon which secondary or tertiary treatment depend.

Urban runoff is another significant source of water pollution, especially in developed countries. In all urban areas (in particular where construction is taking place), sediments are swept up by rainwater or collected in underground or surface storm water channels and then discharged into water bodies. In residential areas, rainwater and storm waters wash over concrete, lawns, cars and buildings, carrying numerous types of pollutants to the freshwater system. Urban runoff in residential areas typically carries fertilizers and pesticides used for lawn care, and also washes dust, heavy metals and oils from the streets into the freshwater system.

Municipal solid waste and garbage are commonly collected and deposited in solid waste disposal sites which, if improperly constructed or maintained, can be a significant source of water pollution. As with industrial waste disposal sites, in the absence of landfill liners and leachate detection and collection systems, natural agents, especially precipitation, can cause pollutants rich in organic substances and toxic chemicals to dissolve in groundwater and leach from solid waste disposal sites. Solid wastes and trash not properly collected and managed may also be carried into freshwater systems by surface water runoff.

Finally, urban areas contribute to water pollution through sources related to transportation. Airborne chemical emissions from transportation activities settle into freshwater systems and contribute to water quality problems. Groundwater and surface water alike receive a considerable amount of pollution from such transportation-related problems as oil and gasoline spills, application of de-icing chemicals, road salt, herbicides, impregnation chemicals (i.e. chemicals used to protect and extend the functional life of road surfaces) and accidental discharges from chemical containers. Runoff from roads and parking lots carries litter and sediments together with oil and chemicals that eventually reach water bodies.

2.4. Effects of water pollution

2.4.1. Human health effects

Water serves as a ready pathway for exposure to numerous microbial and contagious diseases. The three major pathways by which water pollution affects human health are direct consumption, indirect consumption and dermal (skin) contact with polluted waters. Because humans need water for drinking, personal and domestic hygiene and food preparation, these are the primary pathways for direct consumption of water pollutants. When people eat animals and plants that have been exposed to pollutants that bioaccumulate, they indirectly consume these pollutants. Dermal contact occurs mainly in people who rely heavily on water for their livelihoods. For example, fisherfolk spend their days in the water, and water is necessary for all agricultural and animal husbandry activities, through which farmers may be exposed to multiple pollutants.

Vulnerable populations, such as children, pregnant women and the elderly, are often most affected by water pollution. Young children, because they have faster metabolisms than adults and do not have fully developed immune systems, generally have the highest risks when exposed to toxic chemicals. The ingestion of polluted drinking water and consumption of food grown with polluted water have been associated with learning impairments and hyperactivity in children. They can also lower sperm count in men and cause immune system disorders, cancer and genetic damage.

Water pollution is particularly problematic in the developing world, where millions of people obtain water for drinking and sanitation from unprotected streams and ponds. Organic pollution is frequently the cause of illness. If wastewater is not properly treated, for example, or if families and communities bathe and wash in water sources contaminated with animal or human excreta, individuals are exposed to disease vectors. Some of the most significant water-related infectious and parasitic diseases include hepatitis A, diarrhoeal disease (such as dysentery), cholera, typhoid, roundworm, guinea worm, leptospirosis, schistosomiasis, salmonellosis and cryptosporidium. The most prevalent and deadly water-associated health problem is diarrhoea. In developing countries, diarrhoeal diseases cause millions of deaths and episodes of illness annually. Although it was traditionally believed that most diarrhoea was caused by faecal-contaminated drinking water, recent epidemiological studies have shown that in some settings other domestic uses of water can pose an equivalent risk (Van der Hoek, 2001).

As stated above, the runoff from industrial and agricultural activities often finds its way into water bodies that are important sources of drinking and bathing water for urban and rural families. Surface and ground waters act as sinks or transportation routes for chemicals, heavy metals and organic substances that can produce cancers, chronic and systemic illnesses, malignancies and birth defects and impair immune system functions (Wu *et al.*, 1999). For example, mercury and lead leaching into the groundwater from industrial activities can cause nervous disorders and diminished mental capacity, and nitrates used in agricultural activities have been implicated in blood disorders.

Nitrates offer an interesting illustration of the human health challenges associated with poor water quality. Nitrates from fertilizers and from human and livestock waste leach into the soil and become groundwater pollutants in many regions. Nitrate itself is a relatively non-toxic substance; however, bacteria in the environment and in the human body can convert nitrate to nitrite, which is very harmful. Infants under six months old (whose digestive systems both secrete lower amounts of gastric acid and have high pH levels), as well as elderly adults (who may have a diminished capacity to secrete gastric acid), can experience bacteria proliferation which can accelerate the transformation of nitrate to nitrite. Nitrite, once in the blood, serves to oxidize the iron in the haemoglobin of red blood cells to form methaemoglobin, which lacks haemoglobin's oxygen-carrying capacity. When methaemoglobin levels are elevated in infants, a condition known as methaemoglobinemia, often referred to as "blue baby syndrome," can result, since the blood lacks the ability to carry sufficient oxygen to individual body cells. Concern over this nitrate-to-nitrite phenomenon led the United Nations Development Programme to assert that nitrate pollution will likely be one of the most pressing water quality problems in Europe and North America in the coming decade, and will become a serious problem in other countries such as Brazil and India if present trends continue (UNDP, 1999).

Polluted water affects people across the socio-economic spectrum, but the poor suffer disproportionately. In rural areas in developing countries, families rely on streams, wells and lakes for all of their water needs and yet this water is often untreated, unfiltered and untested. Small-scale rural farmers may have little choice but to use an array of fertilizers and pesticides to grow enough food to support their families. These chemicals find their way into community water sources, with harmful results. Certain pesticides such as DDT are not only toxic, but can alter chromosomes, and the effects are being observed generations after the original exposure. PCBs have been determined to cause liver and nerve damage, skin eruptions, vomiting, fever, diarrhoea and foetal abnormalities. Unfortunately, communities living downstream from an industrial operation that leaches pollutants into the watershed area may have no other option than to continue to use the water that flows through their village.

2.4.2. Environmental effects

Water pollution impairs not only human health but also the health of plants, animals and ecosystems. Changes in the chemical and physical characteristics of water can degrade the habitats of indigenous animals, cause disease, infertility and death in various animal species (particularly fish and amphibians) and can result in severe ecosystem damage.

Perhaps the most common and significant environmental hazard related to pollution in water bodies is the lowering of the level of dissolved oxygen in a water body. The health of water bodies is measured in terms of dissolved oxygen (DO) and of biological oxygen demand (BOD). The DO in water comes from the oxygen in the air and from the photosynthesis processes of aquatic plants: its level is affected by the turbulence of water as well as by its temperature. Because colder waters contain more DO, thermal pollution can affect DO levels. If water temperature rises as a result of thermal pollution, the level of DO tends to fall.

The more significant impact on DO, however, is caused by the presence of biodegradable wastes. Such wastes are broken down and used as food by micro-organisms such as bacteria. In digesting their "food", bacteria consume oxygen, and the level of DO accordingly decreases. Once the oxygen is depleted, other bacteria that do not need dissolved oxygen take over. Whereas aerobic (or oxygen-dependent) micro-organisms convert the nitrogen, sulphur and carbon compounds that are present in the wastewater into odourless oxidized forms (such as nitrates, sulphates and carbonates), anaerobic micro-organisms produce toxic and noxious substances such as ammonia, amines, sulphides and methane.

Phosphorus and nitrogen are necessary for plant growth and tend to be plentiful in untreated and poorly treated wastewater. Added to lakes and streams, they can cause nuisance growth of aquatic weeds, as well as "blooms" of algae. This can cause several problems. While the blooms are alive, photosynthesis increases dissolved oxygen. But when the algae and weeds die and become biodegradable material, this can increase BOD and contribute to a reduction in DO levels.

Moreover, such nutrients can spur the excessive growth of microscopic floating plants. This process, known as eutrophication, has a range of impacts.[1] The layer of microscopic plants can veil the water surface, making it difficult for larger submerged aquatic vegetation to get the light they need. This can lead to the death of light-deprived plants and to their subsequent decomposition, which consumes yet more oxygen in the water. Apart from its impact on plant life, eutrophication may also render a body of water uninhabitable for most other life forms, and may lead to the death of the water body. This phenomenon most seriously affects still water bodies such as lakes and ponds, but the excessive growth of aquatic plants can also be a problem in rivers, where it can cause siltation, blockage of channels and, in some cases, even de-oxygenation.

In addition to thermal pollution, which, as noted, can render a water body unsuitable for certain species whilst promoting the proliferation of others, excessive erosion is another type of physical pollution which can pose a significant threat to environmental health, particularly in relation to siltation. Silt carried by runoff accumulates in rivers and in lakes, affecting their flow and their capacity. Moreover, silt often contains pollutants such as nitrates or toxic chemicals, which can affect water quality.

Atmospheric pollution also contributes to environmental effects in water resources. The emission of sulphur and nitrogen oxides, along with other gases, can cause so-called acid rain. Rainfall and dry deposition carries these contaminants into water bodies. Indeed, acid rain can effectively destroy still water bodies, leaving them a distinctive clear blue and completely devoid of life. Acid rain can also affect flowing water, although not with the same measure of destructiveness.

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[1] Eutrophication also has implications for human well-being and health. Algal blooms are the source of algal toxins, which are associated with increased incidence of liver and other cancers. If the water is used as a drinking water source, algae can also clog filters and impart unpleasant tastes and odours to the treated water.

III. WATER POLLUTION CONTROL

The primary animating principle for pollution control is prevention, meaning that avoiding pollution is preferable to having to remediate its effects. Policies should therefore be aimed at managing pollution sources in a way that constrains their post-discharge impact on water resources. The next sections discuss first the control of point sources and then non-point sources of water pollution.

3.1. Controlling point sources of water pollution

3.1.1. Why control point sources?

Point source discharges to water bodies are a consequence of human activity. Typical point sources include factories, mines and other discrete industrial or agricultural activities that emit pollutants into the local watershed. The key variables regarding point sources are *what pollutants* they convey to receiving waters and *how much* is conveyed. Because point sources deliver wastewater in concentrated form, they can be quite destructive if the pollution is insufficiently diluted or untreated. It is because of both their destructive potential and the relative ease with which they can be identified and managed that point sources are most often the first objects of water quality regulation.

It should be noted, however, that not every point source discharge is undesirable. From a wastewater management standpoint, the process of capturing and channelling wastewater through discrete conveyances or point sources can be a positive phenomenon: wastewater, in this form, is eminently more treatable and measurable than when discharged via non-point sources. Point sources can also play a positive role in diminishing erosion and preventing siltation – common problems associated with non-point source pollution.

3.1.2. How are point sources currently addressed?

The responsibility for the control of point source pollution has been seen as resting principally with governments, which must enact and enforce regulations and oversee the implementation of pollution control strategies that protect the interests of their citizens. As discussed in Chapter 3, governments use legal and regulatory instruments to implement point source pollution controls. These instruments tend to consist either of command and control or market-based mechanisms such as economic incentives and disincentives to enforce the compliance of factories, mines and other discrete pollution-generating facilities with pollution standards. States may also implement public education and awareness campaigns as part of their efforts to control point source control pollution.

Several preliminary steps are necessary before controls can be implemented on point source pollution of water resources (see Box 6.2). Each is reviewed below.

Box 6.2 - Preliminary Steps to Controlling Point Sources of Pollution

1. assessment of the ambient condition of the water body
2. determination of desired uses of the water body
3. identification of point sources that contribute pollution to the water body
4. definition of effluent requirements needed to maintain or achieve desired water quality characteristics (through technology-based standards or water quality standards)

Assessment of the ambient condition of the water body at issue. Whether point source control programmes are implemented through government regulation or through less formal mechanisms, the starting point is much the same: water quality assessment. This requires an inventory of pollutants present in the water body. Although this is site-specific, countries that have few resources to devote to research can consult inventories of pollutants (and their common sources) developed at international level. For example, the United Nations Environment Programme established the International Register of Potentially Toxic Chemicals in 1977, with the primary purpose of making information on chemicals substances widely available.

Determinations of ambient water quality are often guided by water quality indices, which are designed to indicate the "healthiness" of water. Indices fall into two primary categories: (1) water chemistry-based indices, which assess water quality based on nutrient levels, microbiology, dissolved oxygen and occasionally metals; and (2) effects-based indices, which attempt to gauge water quality by reference to the biological reaction to aquatic pollutants (FAO, 1996). Water managers use these indices to assess the potential for ecosystem dysfunction, to help identify possible sources of pollution and to guide development of pollution control programmes.

Determination of desired uses of the water body. Another step preliminary to control of point source pollution is identifying designated uses for given bodies of water, a task often assigned to state regulatory agencies. Designated uses are usually expressed as desired water attributes (e.g. usable as potable supply, or for fishing, agriculture, bathing, swimming or other recreation), and are ordinarily influenced by both historical use patterns and existing water quality. If, for example, a water body has historically been used for fishing, then fishing will ordinarily be included among its designated uses and pollution controls will be calibrated to this objective. If a water body is not fit to be used for drinking water, then potability is less likely to be included as a designated use. However, water quality goals may anticipate or aim at an improvement in water quality rather than simply maintaining the status quo. Thus, for example, if historical use patterns include fishing but existing water quality is insufficient to allow it, then fishing may be included as a designated use and pollution controls may be calibrated to restoring the water body to the point that it can support safe fishing.

Identification of point sources that contribute pollution to the water body. Once a water body and its pollution sources have been identified, and designated uses for the water body have been determined, the next step is identifying the point sources that are contributing pollution to the water body.

Definition of effluent requirements needed to maintain or achieve desired water quality characteristics. The process of setting effluent standards requires identifying measures that are (1) technically feasible for the activity in question and (2) essential to achieving water quality objectives for the receiving water. The first are known as technology-based standards whilst the latter are water quality standards.

- technology-based standards

Technology-based standards reflect two approaches. The first is pollution prevention, focusing on manufacturing (or other) processes with the objective of applying "cleaner" technology to reduce the amount of wastewater generated in the first instance. The second is pollution control, generating standards based on so-called "end of the pipe" technologies that neutralize or ameliorate pollution after wastewater generation but prior to discharge.

It is common for regulations to require point sources to use the "best available technology," or BAT. The definition of what constitutes the "best" available technology for any given waste-generating process varies by nation, but international guidance is available.[2] The concept of BAT commonly includes consideration of economic feasibility and is sometimes expressed as the "best available technology not entailing excessive cost", or "BATNEEC". Under this formulation, governments take into consideration the costs associated with the installation of new pollution control devices or the upgrading of existing facilities and operating methods, attempting to strike a balance between environmental benefits and financial costs.

A related formulation is the so-called "best environmental practice", or "BEP" standard. As in the case of BAT, the final responsibility for deciding what constitutes BEP rests with national governments. However, general guidelines to be considered for the definition of BEP have also been elaborated at the international level.[3]

A third formulation is the "best management practice" (BMP) standard. This type of standard typically focuses on how technology is managed and operated, as opposed to the choice of technology in the first place. Establishing BMP can be challenging, but it can be of considerable utility in preventing water pollution. BMP can, at least in theory, be elaborated for every activity that contributes to water degradation, from industry to agriculture. As with all of the approaches to technology-based standards, BMP for a given activity is generally established at the national level.

The disadvantage of technology-based standards is that they are usually divorced from consideration of the pollution levels in the receiving water body and how those levels relate to the desired uses associated with it. This is because they focus on the pollution source rather than the receiving waters. For this reason, technology-based standards are frequently coupled with water quality standards that take into account the quality and intended uses of the receiving waters.

In the United States, for example, point sources are required by the Clean Water Act both to meet technology-based requirements and to implement additional measures necessary to avoid a violation of water quality standards

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[2] See e.g. Helsinki Convention, Annex II, 2002.

[3] *Id.*

in the receiving water body. Another example is the European Directive on Urban Waste Water Treatment (UWWT) of 1991, enacted to protect the environment from the adverse effects of sewage discharges and to ensure that all significant discharges are treated before being released into receiving waters. The UWWT sets uniform effluent standards (or percentage reductions in pollutant concentrations) for discharges from urban wastewater treatment works serving a population equivalent of 2 000 or more persons. These standards are flexible, however: the classification of receiving waters is used as the basis for defining the treatment level required for the wastewater.

Another concern with technology-based standards is their revision. The assumption underlying a BAT, BEP or BMP approach is that standards will be revised as pollution control technologies and techniques improve over time. In practice, however, in many jurisdictions these standards remain static. This is due in part to the cost to government of examining and revising standards, and in part to the cost to industry of changing technology (and hence their strong resistance) because of capital already invested in treatment technologies.

- water quality standards

In contrast to technology-based standards, water quality standards (WQS) relate to the characteristics of water bodies, particularly their capacity to assimilate certain substances (or concentrations of substances). WQS are intended to ensure that water quality is sufficient to allow for designated uses and are typically expressed as concentrations of pollutants that cannot be exceeded without impairing water quality. Water quality standards rest on certain basic assumptions, most notably that the environment has a quantifiable capacity to accommodate contaminants. WQS are usually calibrated to the highest designated use, i.e. the use requiring the most pristine conditions. The WQS approach typically considers not only the effects of an individual discharge but also the combination of the range of different discharges into a water body (Helmer and Hespanhol, 1997).

WQS are developed taking into consideration the relative volume of effluent, the volume of the receiving watercourse and any dilution and degradation. Standard setting involves calculating the upper limits of allowable contaminant concentration in the effluent that will permit the standards to be met under all likely conditions. These upper limits are then used to fashion facility-specific effluent limitations which are tailor made for the conditions surrounding a particular outfall. Limits for similar types of facilities vary throughout a country based on local water quality conditions and designated uses (Helmer and Hespanhol, 1997).

WQS may be set either at the national, regional or local level. Where national WQS have been adopted, local standards typically have to meet (and may exceed) those national standards. Because WQS-based effluent limitations are so location-dependent and variable, developing them can be quite resource-intensive, as can monitoring waters for compliance with the standards. Nonetheless, WQS-based effluent limitations represent the surest means of ensuring that water quality objectives are met, and thus are well worth the investment where resources permit.

3.2. Existing weaknesses in controlling point sources

Despite the clear benefits of an integrated approach to controlling point source pollution, in practice most water quality management systems rest on the development of generic regulatory norms without full consideration of watershed contributions and implications. Another common weakness is a lack of basic state capacity to monitor and enforce compliance with pollution control standards. Monitoring and sampling work requires both trained personnel and proper equipment. Effective enforcement follow-through requires adequate legal authority and sufficient financial and human resources to allow for the prosecution of violators. Without an effective enforcement programme, polluters have little incentive to comply.

Often, states are unable to access and administer the legal and technical tools necessary to redress non-compliance. It is a challenge for developing and developed nations to inspect polluting facilities; take water samples; analyse samples; order corrective action; seek financial sanctions sufficient to disgorge the economic benefit of non-compliance; and invoke the coercive power of the courts. Monitoring powers are particularly important, since monitoring is both the basis for enforcement in cases of non-compliance and the means of assessing the effectiveness of approaches taken to protect water resources.

3.3. Legal, market-based and informal control mechanisms

The primary legal mechanism for applying both technology-based and WQS-based effluent limitations at the facility level is a permitting or licensing regime. Such regimes typically forbid pollution without a permit or licence that dictates the applicable effluent restrictions. Beyond establishing effluent limits, discharge permits commonly impose monitoring obligations to ensure compliance with limits, and often require periodic reporting to government agencies regarding monitoring results. Recognizing that effective monitoring and enforcement programmes can be resource-intensive, some countries have found efficiencies through such legal mechanisms as requiring point sources to self-monitor and to periodically self-disclose any violations of pollution limits (thereby reducing the need for inspections). Other countries have empowered NGOs and citizens to bring enforcement actions in court against polluting enterprises.

Financial tools, such as economic incentives for the adoption of cleaner technologies, are also effective at reducing point source pollution. Examples of such mechanisms include incentives such as tax abatements and subsidies or disincentives such as taxes on the use of specific materials in processing.

Raising the awareness of citizens regarding water quality issues can also contribute to water quality improvement. An informed citizenry can apply pressure to encourage polluters to comply with pollution control provisions. When plants and corporations see that being "environmentally friendly" is in their interest, they may be more willing to assume the costs of pollution control. Citizens can influence polluters' actions through their expression of purchasing power, participation in political processes, community group organizing and legal actions to enforce compliance.

3.4. Controlling non-point sources of water pollution

3.4.1. The challenge of non-point sources

Addressing pollution that derives from sources that are neither readily identifiable nor easily contained is one of the most vexing problems for water quality management. To provide one example, consider the problem of pollution that comes from parking lots. Storm water that runs over parking lots picks up (1) oils and residues that have dripped from cars' engines; (2) oils and tars from the pavement itself; (3) substances that were on car surfaces that have been washed off by rain (not only air pollutants, but also soaps and waxes used to clean and polish cars); (4) solid wastes and litter in the parking area; and (5) contaminants deposited on the parking lots by polluted air. All of these substances are carried into streams by the storm water and pose a serious threat to water quality.

Agriculture is one of the most common and substantial contributors to non-point source pollution. Pesticides, herbicides and fungicides are used in agriculture to kill pests and to control the growth of weeds and fungi. These chemicals can contaminate water through direct application, runoff, wind transport and atmospheric deposition. As described above, these chemicals can kill fish and wildlife, poison food sources and destroy the habitat that animals use for protective cover.

3.4.2. How are non-point sources currently addressed?

Few countries have mastered non-point source water pollution to the same extent as point source pollution, because the challenges are greater. Just as in the point source context, non-point source control necessarily begins with an assessment of water quality and a determination of the uses desired of a given water body. The next step, identifying the significance of the non-point contribution to a given watershed, is a complex process that involves analysing pollution levels in the watershed, calculating pollution loadings from point sources and then subtracting the point source contribution on a constituent-by-constituent basis, with the difference presumptively representing the non-point source contribution of pollution to the watershed. This can require extensive modelling.

Even in countries where major strides have been made in addressing point sources of water pollution, effective management of non-point sources remains a significant water quality challenge. Where the non-point sources for the watershed are identifiable, control efforts typically focus on the use of BMP for the entities responsible for the pollution. In the context of storm water management, BMP includes preventing storm water from coming into contact with problematic drainage areas; reducing the presence of pollutants on surfaces in drainage areas; and managing storm water before it is discharged into surface waters. For the parking lot example above, BMP might address such elements as parking lot construction and design, the use of disposal receptacles for solid waste and methods for containing and treating storm water runoff from parking lots before it reaches any water resources. In the agricultural context, BMP tends to focus on the manner in which pesticides, herbicides and fungicides are stored and applied, as well as mandating mechanisms for channelling and treating agricultural runoff and discouraging the overuse of such chemical compounds.

3.4.3. Existing weaknesses in controlling non-point sources

There are several barriers to effective management of non-point source pollution. First, as noted above, it is difficult to determine the non-point source contribution to water quality problems and to identify the specific contributions of individual non-point sources. Without such identification and determination, effective control is a challenge.

Second, even when "sources" are identifiable, the root causes of the contamination associated with those sources are often substantially attenuated from the discharge itself. Runoff from a highway is an example. Although the source of the runoff may be clear, many of the contaminants within the runoff are by-products from the trucks and automobiles that use the highway, and the production of those by-products is influenced by characteristics of automobile lubricants, the design of automobile engines, the composition of soaps and waxes used on cars, etc. Similarly, in the agricultural context, a complete answer to the problem of non-point source pollution requires a focus on the products whose use causes the problem (fertilizers, herbicides, pesticides) and the manner in which they are manufactured and applied.

Another slightly different example of an attenuated cause is land deposition of airborne contaminants, which are then picked up by runoff. Although regulation of air pollution is common, and although there are examples of air pollution controls induced in part by water quality considerations (e.g. regulation of sulphur dioxide to reduce acidification of lakes), most air pollution standards are based on ambient air quality or technology-based approaches. It is still rare for air pollution controls to be based on non-point source water pollution considerations, leaving this an often unaddressed dimension of the non-point source problem.

Although there have been some successes in regulating products that have significant non-point source pollution potential (e.g. banning or restricting phosphates in detergents, or phasing out certain pesticides), most pollution control efforts to date have focused on controlling and treating discharges rather than on product redesign. Reaching far back in the life cycle of products to influence their design or composition as a means of ultimately influencing the waste streams the products generate is often beyond the scope of pollution control. Nonetheless, the failure to address such attenuated root causes of non-point pollution puts enormous pressure on storm water collection and treatment which, as noted, is a major challenge.

Third, the management of non-point pollution is closely related to land management and land use planning. Decisions regarding what types of activities should occur within given land use areas (such as where and how buildings and roads are constructed) have important effects on non-point source discharge patterns. Unfortunately, non-point source implications are rarely factored into land use planning and management.

Fourth, water scarcity and inefficient irrigation activities greatly affect non-point source pollution. For example, in arid areas where rainwater does not carry residues deep into the soil, excessive irrigation can concentrate pesticides, nutrients, disease-carrying micro-organisms and salts in the top layer of soil, where they pose a greater risk of reaching water systems via erosion and runoff. The failure to address irrigation-related water quality issues as part of the overall strategy for non-point source pollution can be a significant gap in programme coverage.

In sum, there are a number of difficult barriers to constructing an effective non-point source pollution control programme. Yet, given the enormous impact of non-point source pollution on water quality, all these challenges must be confronted and overcome. An effective approach to non-point source pollution requires integrated efforts across a broad spectrum of sectors and stakeholders and on a number of different planes. Legal and policy reform is often necessary to optimize such integration.

3.4.4. Needed policy and legal reforms

Integrated water resource management (IWRM). Non-point source pollution is a challenge that often surpasses the capacity of governments to address and thus calls for other innovative strategies. IWRM is a starting place for overcoming non-point source pollution, as it uses an inter-disciplinary analytical framework that, among other things, considers the linkages between water as a degradable natural resource and the socio-economic value of water. IWRM has great potential as a rationalizing and harmonizing force in water management and planning, particularly in view of its goal of considering the full range of stakeholders relative to a water resource, including dischargers (both point and non-point), water users and land use planners. The key types of integration essential for non-point pollution control are described below.

- *watershed integration*

Just as in the point source context, an effective approach to non-point source pollution requires that water quality problems be examined through a wide-angle lens that considers both the totality of discharges to a watershed and the relative impacts of all contributory discharges. Discrete and targeted interventions that are not part of a broader watershed strategy may have positive localized results but often fail to produce sustained gains simply because watersheds are themselves integrated ecological systems. As such, degradation in any part of the system has unavoidable implications for the entire system. The preparation of basin-level inventories of pollutants – and of the sources of those pollutants – can be key to an effective integrated approach.

- *pollution integration*

Because most types of pollution eventually become water pollution, a truly integrated approach will need to consider pollution that is not "water pollution" *per se*. Airborne contamination that is ultimately deposited on water, or on land subject to runoff, are examples of these. In view of such pollution synergies, it is vital to develop an integrated policy which, rather than treating land, air and water separately, instead considers all pollution that, irrespective of its starting point, may affect water quality in a given watershed.

- *planning integration*

To regulate water resources comprehensively, land use planning and land management need to anticipate and address water quality impacts associated with development activity. For example, an effective tool for the control of non-point pollution is the creation of buffer zones, i.e. the delineation of areas in which activities that might cause pollution are either precluded or at least strictly regulated and monitored. Geographic concentration of certain kinds of activities through zoning or other land use restrictions can allow for efficiency in discharge collection and treatment, as in the case of sewage treatment plants.

- *social integration*

A key tool for the reduction of non-point pollution is public education and awareness. The behaviour of every individual in society has water quality implications, and the potential for achieving water quality improvements by changing social attitudes and behaviours should not be underestimated. If public education cultivates a societal ethic that favours environmental stewardship and protection, it may greatly influence and improve consumer choices, public consumption and public waste production patterns.

The involvement of citizens and local institutions in water management and pollution control is also vital. Education and awareness-raising strategies can help to foster a shift from a purely top-down approach run by national governments to the development of basin-level authorities active in the creation and implementation of pollution control policies specific to the peculiarities of each basin.

Best management practice (BMP). Increasingly, BMP reference points are available for particular forms of non-point source pollution and should be harnessed. For example, in the irrigation context, farmers can both improve water use efficiency and reduce irrigation-related pollution by calibrating water consumption to actual crop-related water demands (Verona *et al.*, 2000). Similarly, integrated pest management techniques can be used to reduce farmers' reliance on chemical pesticides (Verona *et al.*, 2000). Another example is animal farming and aquaculture: discharges from such facilities can be limited by collecting, storing and treating wastewater and runoff prior to their discharge into receiving waters (Verona *et al.*, 2000).

Effective standard setting. The establishment of effluent limits based on BAT and water quality considerations and the use of BEP should form part of an integrated approach to the prevention, control and reduction of non-point source pollution (Helmer and Hespanhol, 1997). Such limitations and required practices must be expressed in clear terms and given the force of law through legal and regulatory instruments.

Product and process life cycle consideration. Control of non-point source pollution depends to some degree on consideration of the life cycle of products and activities that predictably come in contact with fresh water systems. Examples in this regard include pesticides, herbicides and fertilizers that are carried into waterways by storm water runoff; products that, by virtue of solid waste disposal practices, commonly wash into waterways; and airborne by-products that ultimately return to earth and wash into water sources. Many of these products and by-products are already subject to regulation for other reasons. Injecting water quality considerations into these existing regulatory practices can offer substantial benefits.

IV. CONCLUSION

Policy reforms should address the twin sources of water quality problems: direct, point source discharges and indirect, non-point source contributors of pollution to the water body at issue. Moreover, policies must consider not only the specific water body but rather all water bodies that share a common watershed or basin. Indeed, the lens should be broader still, approaching the issue of water quality in the context of IWRM, considering water as both a natural resource and a social and economic good. It is only when the water pollution problem is examined from this broader, integrating perspective that sources of pollution can be effectively understood and appropriately controlled.

Further advances in point source and non-point source pollution control will depend on this type of integration as well as on improvements in government oversight. This will require sound decision-making by governments in the establishment of effluent standards and effluent limits, and a commitment to ensure that these standards and limits are enacted and enforced. Without integration and oversight, and without widespread stakeholder commitment to protecting and restoring water resources, effective pollution control is not possible.

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7

DRINKING WATER*

Contents

* This chapter was prepared by Guy Howard, Jamie Bartram, David Cunliffe and Christie Popp.

Ensuring access to safe, clean drinking water is one of the principal challenges of water management and a major concern in the developing world. Lack of access to potable water is associated with a substantial burden of death and disease every year. The Millennium Development Goals (MDGs) set the target of reducing by half the proportion of people without sustainable access to safe drinking water, placing the issue squarely on the international agenda.

This chapter explores the political, financial, institutional and technical challenges to the provision of safe drinking water. It then examines policy and regulatory means to increase access to water and to improve its safety. The goal is the formulation and implementation of policies and legislation that ensure the greatest benefit to the most people from available resources. The chapter concludes with a detailed discussion of legislative and regulatory options for drinking water quality standards and laws, drawing on the guidelines of the World Health Organization.

I. DRINKING WATER CHALLENGES

1.1. Political challenges

In the regulation of the drinking water supply sector, the overall objective is to guarantee a supply of water that is safe, reliable and easily accessible (i.e. close to the home and available in workplaces and schools and in public places). Achieving this goal can increase economic and social opportunities for households and for developing countries as a whole. Maintaining its achievement underpins health and economy. Thus, economic development is tied to development of the water supply sector.

All countries face political challenges of one form or another in achieving or maintaining access to safe drinking water. These may come from the profit motive and power imbalances between those that need water and those that have the ability to provide it, for example.

One barrier to ensuring access to water supply is the users' lack of political influence or power. The most powerless are often poor, living in rural and remote areas. Some countries, such as Brazil, have had problems expanding supplies to these disadvantaged groups (UN, 2004b). Political patronage, ethnic bias and religious affiliation may also influence resource allocation, and there is often a tendency to give greater attention to improving services for those already supplied, especially in urban areas, and to give less attention to the rural and urban poor.

A failure to convince decision-makers of the value of extending the social, health and economic benefits of access to safe drinking water can also lead to a lack of political support. In fact, recent reports from Latin America and other developing regions suggest that a lack of political will, coupled with rapid population growth, is primarily responsible for slow progress toward the MDGs (UN, 2004b).

At times, complacency and political indifference in both developed and developing countries can be shaken by crises such as droughts, floods or outbreaks of disease. Such crises often mobilize public demands for political action, providing opportunistic triggers for rapid progress. Such opportunities should be grasped when they arise, but it is ineffective and undesirable simply to wait for such disasters to occur. It is far better to maintain existing services and implement consistent policies and practices toward extending improved access to safe drinking water and sanitation.

1.2. Financial challenges

Financial challenges to ensuring access to drinking water come in two principal forms: the financing of water interventions (typically borne by central or local government) and the ability – or lack thereof – of the poor to pay for water through regular tariff payments. Poor people often pay more for water in absolute terms than wealthy people, yet the latter receive better and more reliable supplies. Poor people pay more because their households often lack access to public water supplies. As discussed in Chapter 1, this means they must buy more expensive water from vendors and other service providers. In rural areas the "cost" may also take the form of time invested in collecting water – especially by women – squeezing out opportunities for other productive activities such as education or employment.

The costs of establishing an initial connection to piped water systems and the tariff systems that require scheduled regular payments exacerbate the burden on the poor. Regular payments may be inconsistent with the earning patterns of the poor, whose incomes may be highly variable and unstable and whose ability to save is limited. To help the poor gain access to expanded services, countries may need to implement financial reforms, including cross-subsidies, flexible payment systems or development assistance. Water utilities, especially in poor countries or poor regions, often struggle to generate sufficient cash flows, hence little funding is available for maintenance or expansion. In Lusaka, Zambia, a prolonged lack of investment led to a breakdown in service provision and an inability to extend services to new settlements (WHO, 2003). Towns and communities in developing countries also tend to have limited access to external financing or funding.

In many countries, existing piped facilities are old and need repair. These facilities leak water and, without maintenance, the costs of supplying water increase whilst the value of the supply system decreases. Water that is lost through leakage and poor metering represents a staggering burden, especially in developing countries. The average rate of lost water has been estimated at 37 to 41 percent in the developing world, with regional rates varying from 17 to 62 percent (Lee and Schwab, 2005). In Nairobi and Mombasa, Kenya, water loss was estimated at 50 percent and 40 percent, respectively (Gulyani *et al.*, 2005).

On the basis of limited data, losses in developed countries are believed to be typically closer to 20 percent or less but vary widely, reaching as little as 5 percent in some cases. The volumes can still be substantial. In 2000, licensed water suppliers in England and Wales reportedly lost 3 000 ML per day, representing nearly half the flow of the River Thames in London (NAO, 2000).

1.3. Institutional challenges

Institutional challenges to ensuring access to drinking water and sanitation include the absence of appropriate agencies charged with overseeing and managing water resources and supplies; poor coordination amongst existing agencies; inadequate capacity; lack of accountability; and a lack of appropriate regulatory structures. Institutional reform in some areas will be required to increase access to safe drinking water and sanitation (UN Millennium Project, 2005).

Governments have a range of institutional and management options to ensure provision of adequate services to all. These vary nationally and locally but generally implicate health, environment and drinking water supply agencies (see Table 7.1). Coordination, with involvement of all relevant sectors, is desirable for effective action in increasing access to drinking water supplies. Public health professionals should be involved from the outset

(Bartram *et al.*, 2005). The health sector needs to be involved in setting policy and elaborating legislation as well as identifying investment priorities.

Traditionally, utilities have delivered water services in a top-down approach through public sector monopolies. Government provision has been criticized because it can be perceived as politicized, bureaucratic, inefficient and isolated from public concerns. Over the past 20 years, two alternative approaches to delivery and coverage have been discussed and debated widely. The first is private sector involvement; the second is increased community management. In all cases, any institutional approaches towards water supply management should be accompanied by an adequate regulatory regime and government oversight.

Table 7.1 - Typical Agencies and Authorities with Responsibilities Associated with Drinking Water Supply

Function	Agencies and Authorities
Abstraction licensing	water resource agency, agriculture agency, dedicated abstraction licensing body, river basin authorities, navigation boards, hydroelectricity generators, water supply agency
Water resource quality	water resource agency, environment protection agency, river basin authorities, health agency, water supply agency, local governments
Drinking water supply service quality	water supply regulator, consumer protection bodies, water supply agencies, health agency, local government
Ancillary services (e.g. plumbing)	professional associations, trade associations, water supply agency
Public health protection	health agency, local government, water supply agency
Licensing of materials and chemicals	certification agency, licensing authority, standards association, health agency, water supply agency

Source: Adapted from Howard and Bartram, 2003b.

1.3.1. Private sector involvement

Private sector involvement in the supply of drinking water and sanitation services can range from privatization of water supply (including associated asset management); through various forms of licensing; to sub-contracting specific tasks or roles to private sector entities. This last is almost universal, and most discussion of private sector participation in fact focuses on various forms of licensing to subcontract specific tasks or roles to private sector entities. various forms of licensing to subcontracting specific tasks or roles to private sector entities. In addition to the simple provision of goods and services, the major forms of private sector participation include:

Subcontracting. The government-owned utility subcontracts with private companies to carry out specific activities such as meter reading, billing and payment collection. Private sector involvement is limited, and subcontracting arrangements are unlikely to stimulate private investment. The government utility retains a high degree of administration and oversight.

Management contract. With a management contract, a private company operates water and sewerage services for a fixed term (e.g. five years), for which it is paid a fee. Management contracts are an extension of subcontracting for services but, as with subcontracting, they provide few incentives for private sector investment. Management contracts only apply to established infrastructure and the government utility retains significant administrative duties as well as responsibility for investments.

Lease ("affermage") contract. With this type of contract, the private sector is engaged for extended periods and accepts broad responsibilities for operation and performance. A private company leases the water supply and sewerage assets for a period of 10 to 15 years and operates them in return for the right to revenues from the customers. The main advantages of this approach are that the private operator has clear performance incentives and has necessary working capital. However, the arrangement remains administratively demanding for the public sector, which also remains responsible for investments.

Concession contract. With a concession contract, the private sector operates and maintains existing facilities and is also responsible for new investments. These contracts are generally longer than affermage contracts (typically 25 to 30 years), which may increase external investment. It also transfers some financial risk to private operators. The best-known examples of this approach are in France (Ballance and Taylor, 2005).

Build-operate-transfer (BOT) contract. Under a BOT contract, the private sector is given a contract to build and operate bulk facilities. This form of private sector participation enables government utilities to divest involvement in major infrastructure construction. Potentially, it can increase private financing for construction and delivery of bulk services and it can transfer financial risks to private companies. However, it has been suggested that, because of reduced oversight, BOT contracts present a risk of substandard distribution systems, operations and performance.

Asset sale. This is the most complete form of private sector involvement, where government sells the company and the infrastructure to the private sector. The best-known example of this approach has occurred in England and Wales. Public perception of asset sales can be very negative and can raise substantial political problems (Briscoe, 1997).

In all these arrangements, government supervision of the private actors is essential to ensure that their commitments are fulfilled and that the quality of service and public health are protected. For example, in England and Wales, licences to supply water can be withdrawn by the government if required levels of service are not maintained. In developing countries, however, the institutional capacity to monitor, evaluate and regulate the private sector is often lacking, resulting in poor provision and service.

Evidence indicates that after a surge of interest in the early 1990s, international private investment peaked in 1997, declined to a low in 2002 and has subsequently slowly regained ground (World Bank, 2009a). Private operators supply water only to an estimated three percent of the population in developing countries (OECD, 2003). These low levels of private participation may be due in part to a focus on persuading international private companies to become involved in supply in developing countries rather than supporting and strengthening indigenous private sectors that may be better placed to deliver sustainable services. On the other hand, there are significant barriers to private investment in drinking water supply, particularly in developing regions. These can include low profits, high initial capital costs, extended periods required to achieve financial return, political difficulties in establishing cost recovery and economic and political instability.

Supporters claim that private sector involvement provides opportunities for improved efficiency and better management, and therefore improved access to water. They also argue that it may provide greater private investment funds, creating opportunities to finance new infrastructure that already over-extended government budgets otherwise could not. By contrast, critics suggest that private sector involvement in water supply commercializes a public good and diminishes government involvement in what many see as the provision of a basic necessity, and argue that the claimed efficiencies of private sector participation have not been realized in practice (see e.g. Sierra Club, 2003; Wolff and Hallstein, 2005).

Because drinking water supply is perceived as a basic service essential to health and well-being, the public may expect water to be provided at low or nominal cost, at least to the disadvantaged in order that they be able to afford it. However, to ensure a sufficient rate of return for private investment, water charges (which may have been held at artificially low levels for decades) are usually raised. But marked increases in charges to achieve cost recovery are unpopular and can be politically harmful. An alternative is one that South Africa chose: setting a standard price for a minimum volume and increasing charges in proportion to increased use. This ensures low-cost provision for basic needs. Some jurisdictions have also established independent economic regulators to set fair prices to protect both the private sector investor and the public.

Another fear of private sector involvement is that suppliers may disconnect users as a penalty for non-payment. Amongst other things, this could have implications for health, may impinge on the human right to water (see Chapter 10) and would disproportionately affect the poor. Responses such as reducing flows to provide minimum volumes should be considered for non-payment problems.

Efforts at privatizing municipal water supply in developed and developing countries have been accompanied by strong public opposition. Especially controversial is participation of private interests in policy-making and decision-making. Even the idea that the private sector – meaning companies or other non-governmental associations or corporations – would participate at all in drinking water and sanitation supply decisions has created controversy.

1.3.2. Community management

Direct management of water supplies by communities or local institutions is common in both developed and developing countries and can cover both piped distribution systems and non-piped sources. Supporters of community management suggest that community empowerment, engagement and capacity building are vital to expanding access to improved drinking water supplies. Moreover, management of water and sanitation services at the lowest appropriate level has been identified as a critical action in meeting the MDG targets (UN Millennium Project, 2005).

On the other hand, community management has been criticized because of evidence of low sustainability (high failure or non-functioning rates in infrastructure). It often relies on untrained and sometimes unpaid community members. Some of the perceived weaknesses of community management include:

- lack of commitment to maintaining the water supply and a lack of a feeling of ownership of the supply;
- financial constraints in meeting recurrent costs;
- an inability to demonstrate improvements in water quality and benefits such as improved health;
- community-level committees and local operators lose interest or move away;
- lack of "backstopping" service, such as technical or managerial support.

Community management is unlikely to offer more than an interim solution to system management (Carter *et al.*, 1993). Work has highlighted two key project factors associated with improved sustainability of community management systems: periodic external support to water committees for management issues (e.g. tariff setting and bookkeeping) and technical training workshops for water system operators (Davis *et al.*, 2008).

If community management is to function effectively, the local authority or community must have the authority, financial resources and capacity to deliver the required level of service (UN Millennium Project, 2005). The supporting governmental or non-governmental agency needs to maintain ongoing technical and managerial support. Ownership and responsibilities related to management and operation of community supplies need to be clearly identified, delineated and accepted.

Finally, an appropriate balance must be established between central oversight and local institutions and communities. The central government should be responsible for setting standards and for surveillance and monitoring of community-managed supplies. Regulatory oversight should accompany backstopping support (i.e. such as training and capacity development). In this way, combined systems of community management and government monitoring can be effective (Howard, 2002).

1.4. Technical challenges

In addition to political, financial and institutional concerns, technical constraints can make it difficult to ensure reliable access to safe drinking water. This is true especially in rural communities, as they are widely dispersed and thus present logistical problems associated with installation, management, maintenance and surveillance of drinking water supplies; and in dense urban slums. Wide dispersal may also result in poor communication between centralized agencies in urban centres and local agencies and communities.

Infrastructure developments need to take into account the technical abilities of rural communities. Practical and workable solutions are paramount. There is little point in installing facilities that are beyond the capacity of responsible agencies or communities to maintain. Legislation should take into account the technical capabilities to facilitate implementation.

II. LEGISLATING ACCESS TO SAFE DRINKING WATER

2.1. Drinking water legislation

To address the preceding challenges, a comprehensive legal framework for drinking water can help ensure both progress toward universal access to safe drinking water and a progressive increase in service quality and water safety. The nature of drinking water legislation will vary from country to country and even within countries. It will be shaped by the legal system, the constitutional framework, institutional and legislative arrangements and existing political and regulatory approaches. Because of the complexity of the regulatory framework and the human health issues involved, drinking water is often addressed in separate legislation from that on water resources or the environment.

The content of the legislation will also vary (Howard and Bartram, 2003b). There are, however, some basic issues that must be addressed. Amongst others, these include assignment of authority to responsible agencies, definition of duties of water suppliers, setting of water charges, protection of water sources and enforcement of drinking water quality standards. Ideally, drinking water legislation should also address the political, financial, institutional and technical challenges reviewed above. Legislation should at a minimum aim at ensuring continuity of service, physical accessibility and initially expansion of (rather than improvements to) water service provision. These and other elements of drinking water legislation will be discussed below.

Laws adopted by legislatures tend to be relatively static and can be changed only through an extended process of amendment. Therefore, only the essential provisions should be delineated within the law, leaving the more detailed and technical components for elaboration in regulations, standards, guidelines and codes of practice (FAO, 2005). Water quality standards, for example, may be periodically reviewed and frequently change in a dynamic process (Ince and Howard, 1999).

2.1.1. Basic elements

Assignment of responsibility. A key factor affecting water service performance is whether legislation effectively assigns responsibility to implement and coordinate activities (Kandiah, 1995). To ensure performance, legislation should designate the agencies that will be responsible for ensuring the quality of drinking water supply services. The legislation should clearly delineate their roles and responsibilities in implementing supply and sanitary services and allowing them to operate properly (Smets, 2006).

In particular, legislation should differentiate between who is responsible for providing water supply services and who is charged with compliance monitoring. For example, service quality may be controlled by the supplying agency and independently monitored by a separate agency. Governments may also choose to control or monitor water services through external auditors. Whatever the set-up, it is advisable to establish mechanisms for ensuring that activities and functions are coordinated. This could be through legislation or through memoranda of agreement between involved agencies. Legislation may also decentralize responsibilities, for example to regional or local governments. In the European Union, for example, the responsibility for water service control is in the hands of local governments, not at the Commission or even national level (Smets, 2006).

Water suppliers. Legislation will have to regulate the entities that supply water, which range from large urban suppliers to community-managed suppliers, from independent utilities to local government-run water services to private sector entities. The legislation may establish a licensing scheme, whereby suppliers must apply for a licence (meeting certain prerequisites and agreeing to follow certain conditions), subject to oversight and enforcement by the government.

Legislative provisions should outline the responsibilities of suppliers both in times of normal operation and during emergencies. For example, legislation may provide performance indicators within licence conditions, such as requirements for water quantity, water pressure and consumption; efficiency of supply including controls on leakage; continuity of supply including specifications relating to service interruption (length of time and frequency); coverage and accessibility including requirements relating to extension of supply; and minimum service standards for how to deal with customer complaints and response times.

Legislation may also impose certain limitations on the scope for the private sector to acquire or manage water supplies. It may also set conditions for when water supply services move from the public to the private sphere and vice versa (Smets, 2006). Some countries, including Belgium, the Netherlands and Uruguay, have imposed conditions to prevent privatization of the water supply altogether.

Water pricing. Only a few countries today provide water for free (e.g. Ireland); most charge for the provision. Where water is free or subsidized, the costs of supply are typically borne through taxation. More frequently, legislation implements flat rate tariffs, social tariffs or progressive (consumption-based) tariffs.

Flat rate tariffs take into account the household size, the location of the home or property, the property value and the number of faucets in the home (Smets, 2006). Thus, a family living in a large home in a wealthy neighbourhood pays a higher rate than a family living in a small home in a poor neighbourhood. Legislation may also set up a social tariff, which varies depending on additional factors such as the composition of the family and their income, as well as the amount of water they consume (Smets, 2006).

Some countries (e.g. Mali) have included in their social tariffs reduced rates for whole categories of people.

Progressive tariffs start at a certain price for a minimum amount and increase with the amount of consumption. Progressive tariffs are common and can be found in the legislation of Argentina, Belgium, India, Italy, Uruguay and some locations in the United States. A progressive tariff can also be combined with a quota system, whereby the legislation establishes a free, minimum amount, whilst every unit of water used over that amount incurs a charge (e.g. Colombia, South Africa) (Smets, 2006).

Monitoring and reporting. Legislation should require periodic reporting to regulatory agencies, including health agencies. This should be a requirement whether water supplies are operated by government or by the private sector. Monitoring and surveillance are particularly important for rural populations in developing countries, who receive water through diverse means of supply and infrastructure, many of which have a high failure rate.

Reporting to consumers should also be required. Legislation should ensure that the public at large may obtain (or shall be provided with) information about the water supply, such as the number of households served, the quality of the water, the continuity of services and the tariffs set. An additional provision may require financial reporting on the water services. This may include stating the types of funds the suppliers are receiving and from what sources, the tariff structures and the actual cost of provision.

Public participation. The legislation may address public participation in water supply provision. For example, users may be called upon to provide comments on proposed regulations or agency actions. In most developed countries, the introduction of new standards relating to drinking water quality and treatment requires extensive public consultation before adoption. In developing countries, a standards agency, rather than the regulatory body, often sets standards and consultation may be limited – for example to an expert group. Legislation may also require that the public be represented on government and private-service supplier commissions. For example, France and New Zealand have legislated to allow users of water services to participate in certain management and administrative decisions (Smets, 2006)

Finally, legislation should provide remedies for members of the public who claim violations or infringements of their access to water or service quality.

This might include remedies for improper cut-offs, over-charging or poor water quality.

Protection of water sources. Many activities affect water quality, such as agriculture, mining, forestry and human settlements. The goal of legislation and regulation in this area is to minimize adverse impacts by protecting water sources, thus preserving drinking water quality.

Most often, the protection of water sources is regulated through environmental laws which are enforced by the environmental protection agency in conjunction with agriculture- and industry-related agencies. Legal provisions may set up protection zones around water sources and establish mechanisms to prevent access to surface water sources. Other legislation, such as land laws, may establish restrictions on land use near water sources. Water resources laws generally establish systems to license and monitor water abstractions (see Chapter 5) and to regulate pollution discharges (see Chapter 6).

Drinking water quality standards. Drinking water should be safe to drink. Thus, legislation should identify responsibilities for assessing systems, ensure their management so as to guarantee delivery of safe water, set standards and establish mechanisms identifying and acting on deviations from those standards. Monitoring requirements, responsibilities and actions in the event of non-compliance with standards should also be identified.

2.1.2. Measures to ensure access

Prioritizing drinking water. Wherever the drinking water provisions are located, a statement of purpose and intent concerning protection and support of public health through provision of safe drinking water to the general population will underscore the importance of universal safe water supply. Many countries prioritize water uses within their legislation, and governments will normally want to ensure that the highest quality resources are set aside for drinking water. In times of drought or water scarcity, governments may have to curtail certain uses. Legislation should clearly state that other uses will be prohibited or limited before any restrictions can be placed on essential domestic uses (e.g. drinking, cooking and hygiene).

Ensuring continuous supply. In many countries, if a user does not pay his or her water bill, the supplier is permitted to cut off the water supply to the home (or business). These cut-offs can have disastrous effects on human health and hygiene, and they run counter to a country's efforts at ensuring access to all.

To ensure a continuous supply of water, legislation can limit cut-offs or institute alternatives. Where cut-offs are permitted, laws should specifically designate which individuals or organizations cannot be cut off from water supplies (Smets, 2006). Legislation may also identify the types of cut-offs that *are* permitted, if any, such as to second homes and uninhabited homes. In these cases the risks to human health are lower. Because protection of human health is ultimately a government responsibility, it alone (not the companies or non-governmental organizations involved in distributing water) should determine which users are the most vulnerable (Smets, 2006). This is because water distributors, as a general rule, are likely to have the financial interest of the business or service foremost in mind rather than guaranteeing universal access even to those who cannot pay.

Governments may also adopt alternatives to ensuring a continuous supply of water. For example, legislation may prohibit complete water cut-offs but allow water distributors to limit supply to sufficient minimum levels. Governments could also cover the costs of water supply to the poor, or could require the construction of public fountains where people could obtain their water requirements (Smets, 2006).

Ensuring a continuous supply is an especial challenge during emergencies. For example, if there is a flood or drought and the water infrastructure is out of service, water may be provided through tanker trucks, bottled water deliveries or other alternatives. Legislation should specify whether government, utilities or users will cover the cost of such supplies. Poor users may be disproportionately affected by additional costs.

Guaranteeing physical accessibility. Availability means more than a continuous flow of water. To be available for use by all, water supplies need to be physically accessible within a short distance from the home. One way to ensure physical accessibility is to increase the number of water access points, especially for land occupiers (such as those in shantytowns) who may be residing on property without legal deeds (Smets, 2006). Governments could increase supply points by encouraging construction of public street fountains, allowing access to fire hydrants and "water kiosks" or providing water through tanker trucks.

Expanding rather than improving service. Financing is often an issue when dealing with the expansion of water supplies. To ensure that everyone has access to the necessary minimum amount of water, legislation should state that supplies should be expanded to those without present access before existing supplies are improved.

2.1.3. Bottled water

Bottled water is typically high in cost and is not considered a reliable supply of safe water for domestic purposes since volumes purchased are typically limited to consumption or part of the consumption requirement only. Nevertheless it is seen as an important source of "safe" water by some population groups and at certain times (during travel, for example).

Bottled water is typically regulated as a foodstuff and the corresponding requirements are found in food-related rather than water supply service-related legislation. This can lead to inconsistencies. The Codex Alimentarius Commission of WHO and FAO (Codex) has established a recommended code of hygiene for the safe manufacture and distribution of bottled waters and two standards for the quality of bottled water – one for mineral waters and the other for non-mineral waters. These cover the range of commercial packaged water by setting quality standards to be followed by producers and resellers. They describe the product's characteristics and its composition, including limits for certain chemicals, as well as hygiene, packaging and labelling requirements.

The reason for the distinction between natural and treated water is because of the important value that certain cultures place on the perceived "healthy" properties of some high mineral content "natural" waters. The Codex standard for waters other than mineral waters is generally aligned with the recommendations of WHO guidelines (2008). The Codex standard for mineral waters permits concentrations of some substances to exceed concentrations considered by WHO to be suitable for life-long consumption. In the developing world, a rushed implementation of Codex standards for packaged waters for international trade in order to access foreign markets may lead to distortions internally – by diverting resources from control of the safety of drinking water supply to the control of bottled/packaged water.

2.2. Framework for safe drinking water

The goal of drinking water legislation is to guarantee access to safe drinking water. "Safe" drinking water means water that does not represent a risk to health over a lifetime of consumption. To ensure that water is safe, legislatures and agencies must set standards for water quality and makes sure that these are monitored and enforced.

The World Health Organization (WHO) developed its Guidelines for Drinking-water Quality (2008) to help countries establish standards for drinking water safety. The guidelines outline a preventive, risk-management approach to ensuring that drinking water supplies are safe. The framework is based on meeting defined health-based targets. These targets can be met by implementing a management plan that incorporates control measures to prevent human exposure to microbial and chemical hazards. The framework also incorporates a requirement for independent surveillance to ensure that the management plans operate effectively.

The guidelines represent a consensus around evidence from accepted best practice and sound science. They represent the scientific point of departure for national authorities developing drinking water standards and regulations based on prevailing environmental, social, economic and cultural conditions. The approaches adopted by national authorities vary. Some have used the guidelines as supporting information or a scientific starting point in developing national guidelines or standards whilst others have adopted the WHO guidelines as *de facto* standards. Jurisdictions may have mandatory standards (e.g. United States of America, European Union) or establish non-binding guidelines (e.g. Australia, Canada).

The process of setting water standards needs to be transparent, and the negotiations between regulators, suppliers and the public need to take into account social demands for protection of public health and public perception of risk. Priorities should be established after identifying key parameters, setting appropriate standards for the parameters and ensuring that compliance will be monitored. Because the WHO guidelines list nearly 200 chemicals, some of which may not be universally relevant, countries must assess their local conditions and select the most appropriate standards for their circumstances.

Water quality standards usually include levels or limits of pollutants or microbial and chemical agents that are allowed per unit of water depending on the use of that water. Adoption of less stringent interim standards may encourage progressive improvement of water safety. Interim standards include introducing chlorination immediately followed by progressive increases in water treatment or setting an initial target for a chemical such as arsenic as a first step to minimize significant health risks (AusAid, 2005). Interim standards may be appropriate where water quality problems require significant upgrading of water infrastructure that will take an extended period of time or require large-scale investment.

Relaxations or exemptions are useful for parameters of lesser health concern. This could take the form of allowing a percentage of samples to exceed a standard. The relaxation or exemption could be time-limited and linked to an agreed and defined programme of action to address water-borne hazards.

2.2.1. Health hazards

Microbial hazards, pathogenic bacteria, viruses, protozoa and helminths that cause infectious disease represent the greatest concern for public health. Many of these pathogens in water come from human or animal excreta (faeces). Some of the organisms such as *Legionella* and mycobacteria grow in piped water distribution systems, whereas others such as *Dracunculus medinensis* (guinea worm) occur in source waters. These pathogens are transmitted primarily through ingestion of contaminated drinking water, but illness can also be caused by inhalation of contaminated water (e.g. *Legionella*, *Naegleria fowleri*) or by contact (e.g. *Schistosoma*, *Burkholderia pseudomallei*). For diseases such as schistosomiasis, the availability of safe drinking water reduces contact with contaminated sources and thus helps prevent disease. Table 7.2 sets out microbial hazards that can be water-borne.

Drinking water guidelines and standards have traditionally defined microbial quality based on bacterial indicators of faecal contamination (thermotolerant or faecal coliforms and *E. coli*), the premise being that the major risk to human health is the presence of faecally-borne organisms. These bacterial indicators have significantly contributed to the assessment of water quality and the protection of public health.

These indicators are not perfect, however. Although the use of faecal indicators has been important in promoting water safety, indicators are less directly associated with non-bacterial pathogens. Some viruses and protozoa may survive for longer periods in drinking water than the bacterial indicators and may therefore be present in the latters' absence. Disease outbreaks have arisen from drinking water without indicator organisms being detected (Craun *et al.*, 1997).

These limitations and others have shifted attention to broader indicators of contamination, indicators of effective removal processes and evidence of implementation of preventive measures. Protecting water sources from human and livestock waste minimizes the presence of faecal contamination.

The level of groundwater protection can be assessed by sanitary inspection of wellheads to ensure that structures and seals are intact, protection zones are maintained and barriers to prevent surface water seepage are in place (Howard and Schmoll, 2006). Finally, to measure treatment success, disinfectant concentrations indicate the removal of bacterial and viral pathogens, whilst turbidity indicates effectiveness of filtering viral and protozoan pathogens (WHO, 2008; LeChevallier and Au, 2004).

2.2.2. Chemical hazards

The WHO Guidelines for Drinking-water Quality address a broad range of chemical hazards, including naturally occurring inorganic chemicals; industrial chemicals; agricultural chemicals; water treatment chemicals and infrastructure materials; pesticides used in water to protect public health (e.g. larvicides); and cyanobacterial toxins. Few chemicals in drinking water have been clearly associated with large-scale health effects, although two notable exceptions are naturally occurring fluoride and arsenic (WHO, 2008).

The principal focus for setting guideline values and standards for chemicals has been to identify concentrations that are considered to represent "safe" levels. Chemical standards are set based on whether they have a "threshold" or "non-threshold" effect. The threshold is the level above which a chemical may cause an adverse effect and, conversely, below which no adverse effect occurs.

For chemicals that have a threshold effect, the guideline's numerical values are based on concentrations of the chemical that will have no adverse effect over a lifetime of exposure. By contrast, non-threshold chemicals are harmful at any level; hence there is no threshold level at which an adverse effect can be avoided. Non-threshold chemicals are largely genotoxic carcinogens (cancer-causing agents). Numerical standards for these chemicals are based on concentrations that represent a perceived tolerable risk (10-5 excess risk of cancer from lifetime exposure) (WHO, 2008).

Table 7.2 - Water-Borne Microbial Hazards

Pathogen	Infectivity	Primary Source	Route of Infection
Bacteria			
Burkholderia pseudomallei	Low	Natural	Contact
Campylobacter	Low	Faecal	Ingestion
Escherichia coli pathogenic	Low	Faecal	Ingestion
E. coli enterohaemorrhagic	High	Faecal	Ingestion
Legionella	Low	Natural	Inhalation
Mycobacteria (non-tuberculous)	Low	Natural	Inhalation/contact
Pseudomonas aeruginosa	Low	Natural	Contact
Salmonella typhi	Low	Faecal	Ingestion
Other salmonellae	Low	Faecal	Ingestion
Shigella	Moderate	Faecal	Ingestion
Vibrio cholerae – toxigenic	Low	Faecal	Ingestion
Viruses			
Adenoviruses	High	Faecal	Ingestion/respiratory
Enteroviruses	High	Faecal	Ingestion
Hepatitis A	High	Faecal	Ingestion
Hepatitis E	High	Faecal	Ingestion
Noroviruses and Sapoviruses	High	Faecal	Ingestion
Rotaviruses	High	Faecal	Ingestion
Protozoa			
Acanthamoeba	High	Natural	Contact
Cryptosporidium	High	Faecal	Ingestion
Pathogen	**Infectivity**	**Primary Source**	**Route of Infection**
Cyclospora	High	Faecal	Ingestion
Entamoeba histolytica	High	Faecal	Ingestion
Giardia	High	Faecal	Ingestion
Naegleria fowleri	High	Natural	Nasal passages
Toxoplasma gondii	High	Faecal	Ingestion
Helminths			
Dracunculus medinensis	High	*Cyclops*	Ingestion
Schistosoma	High	Aquatic snails	Contact

Source: WHO, 2008.

2.3. Health-based targets for drinking water quality

Water quality standards are generally based on health-based targets, which define drinking water safety and set the benchmarks for water suppliers, public health officials and the population served. Health-based targets can gradually improve the drinking water supply. The targets should be part of overall national public health policy and should therefore be set by a government. Health-based targets need to be realistic and relevant to local economic, social and cultural conditions and take into account financial, technical and institutional resources. Targets should also consider factors such as existing health burdens, current water quality and accessibility and availability of resources, including user willingness and ability to pay. The judgment of what is considered a tolerable risk is for each country to decide.

In developed countries, the debate about water quality requirements, setting of standards and appropriate levels of risk generally concerns an extensive drinking water infrastructure that has been installed in all but possibly some rural and remote areas. The key financial and technical challenges in these countries often relate to efficient management of existing systems, including rehabilitation, replacement and enhancement strategies in the pursuit of progressively improved drinking water quality. In some cases, attention may be focused on increasing the range of hazards addressed, although some may be of limited health significance. A common theme in developed countries has been a marked increase in the numbers of regulated contaminants. For instance, the number of contaminants regulated by federal drinking water standards in the United States increased from less than 20 to more than 100 between 1963 and 1993 (NRC, 1997).

The circumstances in middle income and poor countries differ because these nations have incomplete water supply infrastructure and higher numbers of people with limited access to drinking water. Thus, to make the best use of resources for the public benefit, these countries must allocate their resources both to expanding supplies and ensuring that safety standards are met. Extending access to improved water sources with low public health risk could be a higher priority than ensuring that stringent standards are met in supplies serving smaller numbers of people. There are ethical and political dimensions to consider when adopting lower water quality requirements, although care must be taken to ensure that debates over such issues are not dominated by well-served elites.

Different types of health-based targets include the following:

Health outcome targets can be established where the burden of disease is measurable and the target is defined as a quantifiable reduction in the level of disease. Health outcome targets are primarily applicable to microbial hazards and chemicals with clearly defined health impacts (e.g. arsenic). Measurement may be through epidemiology studies and surveillance or be based on quantitative risk assessments.

Water quality targets generally take the form of numerical values – for example national standards or guidelines for chemicals.

Performance targets are generally applied to the control of microbial hazards, but can apply to any system where reductions in or prevention of contamination can be measured (through treatment performance or source protection measures). Targets are often based on required removals of pathogen groups or reduction in chemical contamination (e.g. in arsenic or fluoride removal systems) and prevention of recontamination.

Specified technology targets are generally applied to small community supplies and to household-level devices. They can take the form of approved technologies to be used in certain circumstances (e.g. requirements for chlorination), specific control measures such as protection of wellheads and construction standards.

2.3.1. Water safety plans

Health-based targets provide the benchmarks to ensure safe drinking water. These targets are achieved through the design and implementation of preventive risk management plans, which in the WHO guidelines are called water safety plans (WSPs). WSPs and other related risk management approaches are intended to prevent problems before they arise. WSPs also identify potential contamination sources and select and implement appropriate control measures to remove hazards or reduce them to acceptable levels. Moreover, WSPs monitor the control measures to ensure that they remain operational. Traditional end-point monitoring is retained but not used as a primary management tool. Rather it is used to verify that the management systems are correctly designed and implemented and result in the provision of safe drinking water.

WSPs may be applied to all types of systems regardless of size or complexity. Each plan will reflect the nature of the water supply: small systems generally require simple plans, larger systems, more complex ones. General guidance has been developed for the design and implementation of WSPs (Bartram *et al.*, 2009), and formal and informal networks have been established to support implementation of WSPs in large systems, small community supplies and households (WHO, 2009).

Operators of large systems, particularly in developed countries, generally have sufficient resources and the capability to design and implement WSPs, although guidance published by WHO (Bartram *et al.*, 2009; WHO, 2005a) can still help. Implementation of WSPs is more challenging in developing countries, but emerging experience shows positive results (Howard *et al.*, 2005).

Operators of smaller supplies, including those under community management, will need additional support (Bartram *et al.*, 2009). Small communities, particularly those in rural areas, receive less attention and resources than larger systems, mainly because of community dispersal over large areas; distances of the systems from local, provincial or national governments; lack of communication and coordination; lack of political influence in national agencies; and lack of local resources available for operation and maintenance. Operators of small community systems may have limited training and in the case of community-managed systems, may be untrained or unpaid volunteers, as already noted. Reducing reliance on end-point testing can mitigate some of these disadvantages, since small rural schemes and household systems will find monitoring control measures easier than traditional monitoring. In these circumstances, operational monitoring of management systems can be based on observation or the use of field kits (e.g. for measuring chlorine concentrations).

Small systems, whether in developed or developing countries, tend to have poor levels of maintenance and management as well as frequent functional failures. In the United Kingdom, 47 percent of small systems recorded at least one unsatisfactory result in an assessment of water supplies conducted over a 20-month period (Fewtrell *et al.*, 1998). In the United States, during one 27-month period, 23.5 percent of community water systems violated microbial quality standards on at least one occasion (NRC, 1997). Over 600 water-borne outbreaks have been associated with small supplies in the United States (NRC, 1997) and 25 outbreaks for small supplies in the United Kingdom (Said *et al.*, 2003).

There have been problems in large systems, as well. In the United States city of Milwaukee, contamination of drinking water supplies by the parasite cryptosporidium parvum caused over 400 000 people, roughly one-quarter of the city's population, to become ill, and over 100 people died (Corso *et al.*, 2003).

Experience in Bangladesh has shown that WSPs can be implemented in small systems, provided that appropriate support and tools are developed (Mahmud *et al.*, 2007). A number of other countries are developing tools, such as computer-based software as well as written materials, to assist operators or those with oversight of small supplies to implement WSPs (WHO, 2005b). In some cases, generic risk management plans can be developed at central level, with local-level implementation focusing on monitoring and actions to maintain supplies in good sanitary condition (Mahmud *et al.*, 2007).

In addition to developing tools to assist in implementation, capacity building among community supply operators is also needed. Capacity includes education and training for rural communities, mechanisms for providing technical support to local managers of community supplies and measures to increase community support and involvement in the application of WSPs (Bartram *et al.*, 2009).

2.3.2. Household treatment

Around 50 percent of people in developing countries have to transport and store water in the home, thus simple techniques for treating water at home and storing it safely produce large health benefits. Moreover, simple low-cost interventions at the household and community level can dramatically improve the microbial quality of stored water and reduce the attendant risks of diarrhoeal disease and death (Fewtrell *et al.*, 2005; WHO, 2002). Safe storage involves minimizing contamination using storage vessels with narrow openings and using dispensing devices such as taps or spigots.

Although 83 percent of people in developing countries have access to improved drinking water sources, only 42 percent have access through a household connection or a yard tap. The 17 percent with no access to improved water have no choice but to carry water from unsafe sources. Home water treatment and safe storage do not diminish the requirement of access to safe water supplies, but they can be adopted quickly prior to the provision of enhanced infrastructure (WHO, 2002; WHO/UNICEF, 2005).

A range of water treatment technologies have been developed. Examples of technologies that reduce microbial contamination include chlorination, solar disinfection, combined flocculation and chlorination powders and finally, ceramic filtration.

Household water management practices have been introduced in about 50 countries involving treatments ranging from filtration through sari cloth and nylon to commercially produced sachets of flocculants and chlorine (WHO/UNICEF, 2005). A key criterion for management practices is that the materials be locally available and acceptable. In Kenya a solar disinfection project was successful because community members were able to obtain suitable bottles. Also in Kenya, local factories producing ceramic filters reportedly recoup costs within a year of production.

2.3.3. Surveillance

The final component of the framework for safe drinking water is independent surveillance to assess compliance with health-based targets. Broad-based surveillance surveys have been successfully developed in Peru and Uganda (Howard and Bartram, 2005). These surveys include assessment of access to water supplies; use of water sources; water quality; sanitary condition; water quantity; continuity; cost (affordability); and leakage. Both case studies showed that information on these key indicators could be collected in a cost-effective way, which supported management actions that improved water safety. In both cases, the surveillance programmes improved operation and maintenance and household water hygiene. For urban and small community water supplies, surveillance should include approval of WSPs as well as assessment of drinking water quality.

2.3.3.1. Drinking water quality

Surveillance of drinking water quality requires the surveillance agency to audit a water supplier's performance or perform a direct assessment through inspections and independent water quality testing (WHO, 2008). Auditing normally involves reviewing WSPs, examining records to ensure that system management is being performed in accordance with the WSP, checking records to ensure that control measures have operated within prescribed limits and reviewing drinking water test results to check for compliance with specified targets. Audit-based approaches place responsibilities on water suppliers to provide information to the surveillance body, and this requirement needs to be enforceable.

Direct assessment usually includes sanitary inspections of water supply systems (from source to supply to consumers) in addition to drinking water quality tests. For small suppliers, the surveillance agency's direct testing may be the principal source of water quality data. Direct assessment requires technical expertise in sanitary inspections, collecting samples and interpreting results. The surveillance agency will require access to analytical facilities.

Where there are large numbers of community or household systems, frequent direct assessments of all supplies may be impossible. Instead, rolling programmes or well-designed surveys may provide at least overviews of water quality and evidence of general problems. Irrespective of the method of surveillance, the surveillance agency and water providers must communicate and cooperate to maximize the benefits, implement necessary changes and improvements and avoid duplication of effort.

Control of water safety and surveillance of small community supplies present particular difficulties, especially because of the limited capacity of operators to implement management programmes and undertake monitoring. The numbers and dispersal of these systems also raise problems. Surveillance of community-managed supplies is more likely to produce positive outcomes if the emphasis is on providing support to enhance good management. Visits by surveillance agencies may for example include health education and health promotion activities to promote sound management practices. Surveillance can include participatory activities relating to sanitary inspections and testing using field test kits. Where appropriate, visits could also include household storage examinations and stored water tests. Household treatment systems should be surveyed to determine their acceptance, adoption and maintenance.

2.3.3.2. Service level

In addition to assessments of water quality, surveillance should determine levels of service including quantities of water supplied, continuity of supply, accessibility and affordability. The amount of water supplied to households has a significant impact on public health. Estimates of the necessary volumes indicate that basic services require an average of 20 litres per person per day whilst optimal access requires 100 to 200 litres per person per day (Howard and Bartram, 2003a). Assessment of the quantity of water is most effectively carried out using the service level as a proxy, as extensive research has shown that the amount of water households collect is a function of the distance and time taken to collect it (Howard and Bartram, 2003a).

Surveillance should also consider the continuity of supply. Frequent short-term interruptions to supply adversely affect hygiene and lead to increased need for household storage. Short-term interruptions may be caused by restricted pumping regimes, power restrictions or outages, peak demands exceeding system capacity and infrastructure failure (e.g. pump failure, treatment failure, pipe bursts). Climatic conditions and competing uses, such as irrigation, may also cause seasonal water shortages. These longer-term interruptions may require alternative water sources that are inferior in quality or farther away. Surveillance should determine the causes of discontinuity and possible solutions. It should also assess the responsibilities and performance of water suppliers in relation to maintenance and timeliness of repairs. Furthermore, surveillance should identify requirements for infrastructure improvements to reduce interruptions.

Affordability of water affects patterns and volumes of use and the sources of water used. Determinations of affordability should take into account all costs associated with drinking water, including costs of connection to piped water supply and volume tariffs. In addition, any costs of household treatment and storage should be included as well as any costs associated with alternative water supplies, such as those provided by vendors.

2.3.3.3. Surveillance in practice

Evidence indicates that surveillance is under-utilized in developing countries. It also appears that surveillance of piped supplies in urban areas is performed more extensively than in rural areas, but with alternative sources and household water rarely included (Howard and Bartram, 2005).

Surveillance functions and responsibilities will vary according to legal, administrative and technical circumstances at national and local levels. Most surveillance models, including that proposed by WHO (2008), envisage service quality controlled by the supplying agency and independently monitored by a separate surveillance agency. In most countries, the agency responsible for surveillance should be the Ministry of Health and its regional or local offices.

In some countries, a central environmental department may provide surveillance, or it could be decentralized to local government. In the United Kingdom, for example, regulation and surveillance is the responsibility of the Drinking Water Inspectorate, which is part of the Department of Environment, Food and Rural Affairs (Ballance and Taylor, 2005).

Surveillance of the more than 100 000 smaller private suppliers in the UK is undertaken by local government (Shepherd *et al.*, 1997).

Centralized surveillance presents difficulties where large distances and travel times are involved. Centralized surveillance also means there is a physical separation between the surveillance agency and the communities that are being monitored (and are directly affected by unsafe water). The preferred model in these circumstances is surveillance by the local health authority under the guidance of a national health body (Howard, 2002), although independent surveillance of small community supplies in developing countries may be problematic. For example, where local government is the water supplier, separating the function of surveillance is achievable but is not likely to be easy. Legislation establishing surveillance systems should take this into account.

2.4. Legislative implementation and enforcement

Even where appropriate laws, regulations and administrative arrangements are in place, supply of adequate drinking water requires political support and adequate funding and capacity. A common obstacle has been inadequate funding of the primary agencies responsible for regulation and surveillance of drinking water supplies. Without an underlying institutional structure that has both the will and resources to undertake regulation and enforcement, governments cannot implement their drinking water legislation.

Implementation of legislation can be problematic in both developed and developing countries. In a survey of three pilot projects in developing countries, Lloyd and Helmer (1991) noted a lack of strong institutional action. This was also the case in Canada, where a review of an outbreak of *E. coli* O157 and *Campylobacter jejeuni* in Walkerton, Ontario found that regulatory authorities were not actively involved, thus contributing to the deadly occurrence (O'Connor, 2002). A review of a 1998 outbreak of cryptosporidiosis and giardiasis in Sydney, Australia, also made a case for increasing regulatory oversight (Clancy, 2000).

Effective implementation requires that all agencies and authorities relevant to drinking water commit and coordinate their actions, although it is generally recognized that the head of the health ministry or department should take a lead role in oversight and surveillance of drinking water supplies and drinking water quality (WHO, 2008; Bartram *et al.*, 2005). Countries should maintain the balance between central government and local authorities.

Decentralization advantageously places governance and support closer to the community and allows for closer tailoring of regulatory actions based on local needs. Legislation needs to provide the authority and autonomy necessary for decentralized operations to function successfully (Appleton, 1995). The UN Millennium Project Task Force on Water and Sanitation also advocates that governments empower local authorities and communities to manage water supply delivery (UN Millennium Project, 2005).

Even with decentralization, there is room for complementary centralized oversight (Howard, 2002; UN Millennium Project, 2005). Centralized government should take the lead on issues such as standard setting, provision of subsidies and actions to improve access to water supplies. Central government should also maintain oversight of decentralized services to ensure that provision of services is consistent with national policies, particularly in relation to the provision of services to the poor.

III. CONCLUSIONS

The MDGs aim to halve the proportion of people without sustainable access to safe drinking water by 2015. Progress is measured by the WHO/UNICEF joint monitoring programme, which assesses access to improved drinking water supplies (WHO/UNICEF, 2004). The issue of safety is dealt with in the WHO guidelines for drinking water quality (2008), which present a framework for safe drinking water and numerical guideline values for hazards to public health. The framework addresses the setting of health-based targets, the management of drinking water supplies through water safety plans and independent surveillance.

The general principles captured in the WHO guidelines can and should be applied universally. However, the framework of the WHO guidelines is not prescriptive, and the numerical limits are not mandatory. Application of the guidelines should be based on national circumstances including local environmental, social, economic and cultural conditions. This includes consideration of existing levels of access to improved sources of drinking water and available resources.

Determining access requirements and setting water quality targets require careful consideration. Standards for drinking water should be supportive and protective of human health but the targets should not be so restrictive that they represent a barrier to improvement. This would particularly disadvantage the poor, who are disproportionately represented among those without access to improved drinking water sources.

Approaches adopted in developing regions will often be different from those in developed regions, and there will also be differences within regions. Extending access is likely to be a high priority in developing countries, whilst issues relating to management and improvement of existing infrastructure are likely to receive greater attention in developed countries. The approach adopted needs to be delineated in national policies and supported by appropriate legislation, which should be designed to maximize benefits to all sectors of the population. The implementation and effectiveness of the laws and policies should be monitored through an active surveillance programme, and where necessary modified to ensure that required outcomes in the delivery of safe drinking water supplies are achieved.

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8

WATER AND AGRICULTURE*

Contents

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* This chapter was prepared by Jamie Bartram, Sasha Koo-Oshima, Christie Popp, Jessica Vapnek and Jared Gardner.

Agriculture is the principal human use of water resources in the world, with more water abstracted and used for agriculture than for all other uses combined (FAO, 2009a). Although the world's population nearly doubled between the early 1960s and the late 1990s, global agriculture kept pace through the "Green Revolution", whose investments in surface water storage and groundwater extraction enabled many countries to meet increasing irrigation demands.

Future expansion of food production to meet the needs of growing populations will require greater efficiency in the capture and use of water for irrigation. Whether current irrigation practices will ensure food production sufficient to support future population growth will depend on a number of factors, including application of water control and water-efficient irrigation technologies, use of rainwater harvesting techniques and reclaimed water for agriculture, the amount of irrigated land lost over time, competition for water, alterations in dietary habits, climate change and improvements in crop varieties, amongst others.

This chapter focuses on water in agriculture, particularly on increasing water use efficiency by implementing good practices in irrigation and drainage management. The chapter outlines how irrigation and the quest for water for food production can affect human health and the environment. In view of increasing water scarcity, wastewater will increasingly be a valuable resource as it can help reduce pressure on water resources and provide essential nutrients for crops. It can help increase food production whilst reducing the need for synthetic fertilizers. The goal in regulating wastewater use is to maximize the benefits whilst reducing risks to human health and the environment to tolerable levels.

I. ISSUES IN IRRIGATION

Primary production of food requires water, and nearly two-thirds of all freshwater abstraction worldwide (and up to 90 percent in some countries) is devoted to food production. With the world facing growing food scarcity and rises in food prices, identifying ways to increase food production is a key challenge. Meeting this challenge will require increasing water use efficiency and improving crop varieties as the availability of land diminishes. Water managers and law-makers must balance the need for food with the decreasing availability of water in some areas of the world and the expected risks from climate change.

Sustainability of irrigation depends on applying good irrigation practices, water-efficient technologies and water governance. As an example of the last, in some areas up to eight percent of all food crops may be grown on land irrigated with groundwater that is being abstracted faster than it is being replenished (Postel, 1999). Developing more efficient and sustainable methods for the use of water resources is essential.

This section first addresses the way in which irrigation schemes and society influence the amount of food production and the use of water. Second, it addresses how irrigation affects human health. Finally, the discussion turns to how irrigation and the environment interact.

1.1. Food production

Irrigation can play an important role in alleviating poverty and improving food security through its use in food production. Irrigation schemes have been linked to increases in calorie intake and decreases in the numbers of undernourished people. From 1969 to 1971, the intake per person per day was 2 110 Kcal for developing countries and 2 410 Kcal for the rest of the world. From 1997 to 1999 those numbers increased to 2 680 Kcal and 2 800 Kcal, respectively. At the same time, the number of undernourished people in the developing world decreased from 37 to 17 percent (FAO, 2001a).

Food production's negative impacts on water resources can increase with greater economic prosperity. As societies grow wealthier, meat consumption typically increases. Using water to raise crops for animal feed is much less efficient than using it to produce crops for direct human consumption. Producing a kilogramme of beef requires 8 to 85 times more water (depending on soil and climate conditions and irrigation methods) than producing a kilogramme of grain (see Table 8.1).

Over-grazing of livestock leads to more surface runoff of water, causing soil erosion (and reduced soil fertility), eutrophication and less groundwater recharge. Industrial farming concentrates large numbers of livestock in small areas and produces significant quantities of animal waste, which – if not stored and treated properly – can pollute both groundwater and surface water supplies. Moreover, zoonoses (infections transmitted from animals) are the principal emerging infectious diseases threatening human health (Cotruvo *et al.*, 2004). As societies move from a grain-based diet to a meat-heavy diet, they use more water for food production. Globally, it will be necessary to develop strategies to use water more efficiently to maintain or increase food production with limited water resources.

Table 8.1 - Approximate[1] Crop Water Requirements to Produce Specific Foods

Crop/Food	Water Requirement (kg of water per kg of food produced)
Potato	500 – 1 500
Wheat	900 – 2 000
Alfalfa	900 – 2 000
Corn/Maize	1 000 – 1 800
Sorghum	1 100 – 1 800
Soybeans	1 100 – 2 000
Rice	1 900 – 5 000
Chicken	3 500 – 5 700
Beef	15 000 – 70 000

Source: Gleick, 2000.

Gleick (2000) estimates that it takes 640 m^3 of water per person per year to grow enough food to support the average diet of a person living in Sub-Saharan Africa and nearly three times as much – 1 830 m^3 of water per person per year – to grow enough food to support the average diet of a person living in North America (see Table 8.2).

Years of research during the Green Revolution dramatically improved the yield and water use efficiency of many crops. For example, hybrid rice strains were developed that matured earlier and produced approximately three times as much rice per unit of water (Postel, 1999). With more research, further water efficiency gains are possible for some crops. However, even with the adoption of new technologies (e.g. genetic engineering), future increases in yield and water use efficiency for many crops such as wheat or rice are unlikely to be as large as those made during the Green Revolution (Postel, 1999). It may be necessary to focus more research efforts on improving varieties of other crops (e.g. cassava, yams), including some that are important to subsistence-level populations.

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[1] These approximate values also vary significantly by region, climate, irrigation methods and other factors.

Table 8.2 - Calories Required for Regional Diet, Percentage of Diet as Meat, Estimated Water Needs[2]

Region/ Grouping	Calories (Kcal) of Regional Diets (1989)	% of Calories from Meat	Estimated Water to Produce Regional Diet (m^3/capita/yr)
Africa, Sub-Saharan	2 191	10	640
Centrally Planned Asia	2 541	15	920
Eastern Europe	3 345	28	1 430
Former USSR	3 253	30	1 570
Latin America	2 555	19	1 030
Middle East/North Africa	2 819	13	1 070
OECD-Pacific/Oceania	2 691	24	1 210
South and East Asia	2 485	12	770
Western Europe	3 350	36	1 710
North America	3 133	35	1 830

Source: Gleick, 2000.

1.2. Human health

Although the expansion of irrigation schemes has been an extremely important factor in increasing food production, poorly planned and managed irrigation systems may pose risks for human health. The principal risks derive from limitations to or decreases in food production which may affect food security and thereby nutrition; changes to disease vector habitats which may increase disease risk primarily for nearby populations; and contamination of foodstuffs with infectious agents and toxic chemicals from human, animal and industrial wastes and the natural environment.

The principal contaminant concerns for human health are infectious bacteria, protozoa and viruses deriving from human or animal excreta. Irrigation may also allow agricultural inputs such as pesticides and artificial fertilizers to leach into the drinking water supply with potential health risk if concentrations reach levels of concern.

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[2] Includes both rainfall and irrigation water, and assumes variations in regional irrigation efficiencies.

To help prevent or counteract potential harmful health effects of irrigation schemes, irrigation management should also integrate vector control measures. Vector control should address three components: permanent or long-term modification of land, water and vegetation to control vector breeding and spread; ongoing management of land, irrigation and drainage to produce and ensure conditions unfavourable to vector breeding; and the modification or manipulation of human habitation or behaviour (FAO, 1984). In addition to chemicals and vaccinations, measures such as drainage, aquatic weed control, canal maintenance and lining, water management (including intermittent irrigation practices) and human-vector-pathogen contact reduction measures are important and cost-effective components of an integrated vector control strategy (FAO, 1984).

1.3. The environment

Irrigated agriculture may have both negative and positive effects on water quantity and quality. Irrigation schemes that are poorly planned and managed may result in increased salinization, over-abstraction, degraded water quality and loss of biodiversity. By contrast, good irrigation and drainage practices may result in better, more efficient water use and ecosystem protection.

Poor drainage practices can lead to waterlogging and salinization, causing decreased land productivity. Salinization concentrates salts in the upper soil layers where plants root, and can cause yield decreases of 10 to 25 percent for many crops. Salinization may prevent cropping altogether when it is severe. In East Asia, 6 percent of agricultural land is degraded by salinization, whilst in South Asia 8 percent is affected. For the arid and semi-arid tropics as a whole, 12 percent of agricultural land may be degraded (FAO, 2003). These global statistics often fail to convey the localized impacts of these environmental changes on regional food security and environmental sustainability.

In certain areas, irrigation is associated with surface water and groundwater over-abstraction, which can negatively affect the amenity and ecosystem values of water. Wetlands, for example, have contributed to agricultural growth because their soils are fertile, they contain water for much of the year and they help regulate floods and protect biodiversity. However, many wetlands have been extensively drained, which has seriously damaged the environment. This is one of the many factors that led to the adoption of the Ramsar Convention on Wetlands in 1971 to protect wetlands from over-exploitation by outlining principles of wise use. According to the convention, sustainable use of wetlands can be achieved by selecting crops adapted to wetland conditions, using appropriate soil and water management technologies and carefully planning wetland development within an entire watershed so biodiversity is protected from any agricultural activities in upstream areas.

Pollutant loads, habitat degradation and massive water withdrawals arising from irrigation and damming have in some circumstances harmed inland fish resources. Degradation of water quality poses a serious problem especially in estuarine and coastal zones at the lower end of river basins where eutrophication, oxygen depletion, habitat loss and pollution from intensive farming systems have had an impact on natural resource sustainability.

Notwithstanding these challenges, irrigation programmes can help reverse negative environmental impacts by promoting environmentally sound uses of water, proper drainage and irrigation practices and biological treatment of waste. Well-planned implementation schemes and other good agrarian and buffer zone practices can enhance water infiltration into the ground and thereby reduce flood runoff – particularly if the soil is not saturated, the ground is not compacted and the irrigation is part of a conjunctive management programme. Reuse of treated wastewater can reduce health risks further downstream. Moreover, subsistence agriculture and agriculture that is not focused on monoculture can preserve agricultural and natural biodiversity. Irrigated land may also help offset carbon emissions, since certain crops can help absorb carbon that is released into the atmosphere.

II. INCREASING IRRIGATION EFFICIENCY

It is increasingly important to improve the efficiency of irrigation practices in order to reduce water usage and loss at all levels of the irrigation system. Measures to increase water use efficiency in irrigation include establishing and enforcing water allocation rights (see Chapter 5); promoting water conservation; implementing more efficient irrigation systems and adopting on-farm technologies that reduce water usage; developing and planting crops that use less water; and using treated wastewater or land treatment processes for untreated wastewater. Devolving certain management responsibilities to users may also serve these ends. In addition, water resources may be used more efficiently in general when they are part of a larger basin-wide management scheme integrating all uses and needs (see Chapter 9).

Irrigated agriculture's largest losses typically occur when water is routed through canals and ditches to farmers' fields. As it travels, water is lost into the ground through seepage and also into the atmosphere through evaporation. Efforts to reuse drainage water and to prevent these losses will result in real water gains (Huffaker and Whittlesey, 2000). Transmission losses can be reduced by filling sinkholes, lining canal bottoms and sides with either conventional concrete or roller-compacted concrete and replacing canals with high-density polyethylene pipe.

The amount of freshwater used for irrigation can also be significantly reduced by introducing new techniques that address precisely how water arrives at each plant (see Box 8.1). Technologies include drip irrigation, efficient sprinkler systems, precision irrigation, timed water application to match plant requirements and the development of new water-efficient crop varieties (FAO, 2001b; Postel, 1999).

Box 8.1 - Methods of Improving Irrigation Efficiency

Improving the efficiency of irrigation systems is essential to addressing problems of water scarcity and improving the management of water allocations in general. However, irrigation efficiency does not only mean reducing abstractions. Rather, it requires a close consideration of how the water reaches each plant. FAO has developed six management "keys" to improving efficiency in irrigation systems:

1. reducing seepage losses in canals by lining them or using closed conduits (including pipes);
2. reducing evaporation by avoiding mid-day irrigation and using under-canopy rather than overhead sprinkling;
3. avoiding over-irrigation;
4. controlling weeds on inter-row strips and keeping them dry;
5. planting and harvesting crops at optimal times; and
6. irrigating frequently with just the right amount of water.

Source: FAO, 2001b.

Low-cost drip irrigation techniques have been introduced in a number of countries. In the early 1990s, FAO set up a pilot project in Cape Verde which was so successful that a number of private farmers adopted the same drip irrigation techniques. Within six years, 22 percent of all irrigated land in Cape Verde was irrigated with drip systems (FAO, 2001b), and as a result, the production of horticultural crops increased from 5 700 tonnes in 1991 to 17 000 tonnes in 1999 (FAO, 2001b).

These technologies may not be appropriate in all settings, for example where land needs to be prepared or ploughed seasonally. Furthermore, certain technologies may not be appropriate for all farmers: they may be low cost for the average commercial farmer but unaffordable for subsistence farmers, especially considering expenses for system maintenance. Subsistence-level farmers often cannot afford the equipment necessary to use drip irrigation technology and must instead rely on surface water supplies and cruder irrigation diversion systems. For these farmers, more low-cost or low-maintenance technologies or techniques may be appropriate.

Another technique to improve efficiency is deficit irrigation, where crops are not supplied with the full amount of water typically required to achieve maximum growth. Instead the farmer reduces the water application, cognizant of the tradeoffs amongst water availability, plant growth and crop revenue. This approach is particularly useful in arid or semi-arid regions. Field trials have shown that through deficit irrigation, substantial water savings can be achieved with little impact on the quality or quantity of the crop yield (FAO, 2000b). For example, in the North China Plain, water savings of 25 to 75 percent were realized without significant yield or profit loss (FAO, 2000c). On the other hand, a study of potatoes in the United States in the State of Oregon showed that limiting water use had adverse impacts on yields and profits (FAO, 2000a) – demonstrating that techniques that work in one area may not work in another. Still, research on fruit crops in Australia and the United States has shown increases in water use efficiency of up to 60 percent as a result of improved water scheduling (FAO, 2000d; FAO, 2000b).

Water savings during primary production can be achieved by growing more crops during the cool season when there is less evaporation (and in some regions more rainfall) and by better managing fallow land and crops (Seckler, 1996). Water use can also be made more efficient by adapting the water quality to the crop. Seckler (1996) cites an example of using salty drainage water from a crop to irrigate cotton, which is a halophyte (i.e. a salt-tolerant crop). The drainage water from the halophytes – which may have a higher salt concentration than sea water – is then channelled into evaporation ponds and the salt harvested after the water evaporates. Saline or sodic (i.e. high in sodium relative to calcium and magnesium) water from drainage water is used to produce many conventional grain, forage and feed crops and salt-tolerant plants and trees, particularly in Bangladesh, China, Egypt, India, Iran, Pakistan, Syria and the United States. Recently, as areas have been abandoned for agriculture because of waterlogging and salinity, inland saline aquaculture has been adopted on a small scale in several developing countries, as in the Nile Delta of Egypt (Qadir *et al.*, 2007).

III. USING WASTEWATER FOR IRRIGATION

The use of wastewater for irrigation is widespread in developed and developing countries. Wastewater as discussed here generally refers to wastewater generated by human populations.[3] Untreated wastewater is often used in the informal, unregulated sector and directly benefits poor urban and peri-urban farmers who would otherwise have little or no water for irrigation. Much water abstracted from rivers and other water courses contains a significant proportion of wastewater, and "conventional" irrigation from such water courses is for practical purposes a form of indirect wastewater use. Untreated wastewater can improve soil fertility and reduce water contamination downstream (since the wastewater is not fed directly into the water flow but is first filtered through soils during irrigation), but use of untreated wastewater for irrigation presents a risk to the health of the workforce, nearby population and consumers.

This section addresses wastewater management. First, it discusses wastewater's use as a resource, and then outlines social and equity issues relating to wastewater use. It then examines good practices for maximizing benefits from the use of wastewater in irrigation. Finally, the section outlines the underlying legal and regulatory framework for wastewater and briefly discusses guidelines for wastewater use.

3.1. Wastewater as a resource

Planned water reclamation and reuse for agriculture is a strategy gaining wider acceptance in many parts of the world. In water-scarce countries, wastewater services have become important in attaining the equilibrium

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[3] Industry-created wastewater may have serious toxicity problems, but with appropriate treatment may become acceptable for irrigation of some crops. Urban sewerage often receives discharges from industrial sources.

between demand and supply of adequate quantities and quality of water. Increasing population and food demand, water shortages and concerns for environmental pollution have made reclaimed wastewater an increasingly valuable resource.

Use of wastewater requires changes in the traditional water allocation systems, funding structures, water-quality standard-setting, regulatory frameworks and institutional mandates. It involves good governance at all levels in order to develop a holistic approach and consistent policies. Integrated water resources management, because it encompasses all aspects of water resources development, management and use, can be usefully applied in the wastewater context. A key challenge will be to consider both basin-wide issues and local needs together.

The concept of a multiple use approach of water can also be useful in incorporating wastewater use into water resource management, since it is based on the conception of one water resource supporting a variety of uses. Deliberately allowing for multiple uses when designing and managing irrigation schemes can protect users' livelihoods and health. A multiple use approach requires (1) assessing water needs in collaboration with end users; (2) examining the water sources available – from rainwater to wastewater to piped systems; and (3) matching water supplies to needs based on the quantity, quality and reliability of water required for the various purposes (IWMI *et al.*, 2006).

Particularly in arid and semi-arid regions, wastewater is often used in irrigation where it represents an important resource for farmers. In addition to its water content, wastewater contains nutrients and organic matter that facilitate plant growth.[4] At an irrigation rate of two m^3 per year (a typical requirement in a semi-arid climate), treated municipal wastewater can supply 300 kg per year of nitrogen and 60 kg of phosphorous. In such cases, supplementary fertilization needs can be reduced or even eliminated for some crops (Mara and Cairncross, 1989) (see Box 8.2). In addition, since wastewater flows are often consistent across seasons, they offer a drought-resistant source of water (Gleick, 2000).

[4] The nutrients in wastewater can also be useful for aquaculture, which is not a topic addressed in this chapter.

In coming years, population growth will stress water resources, with most population growth expected in urban areas. As urbanization leads to generation of more wastewater, wastewater use can contribute to optimizing water resources and ensuring a dependable year-round supply of water to support urban and peri-urban food production (FAO, 2009a). In Mexico, most of the wastewater from Mexico City is used in irrigation districts surrounding the city (Scott *et al.*, 2000).

Box 8.2 - Agronomic and Economic Benefits of Wastewater Use in Irrigation

A city with a population of 500 000 and water consumption of 200 litres/day/person would produce approximately 85 000 m^3 per day of wastewater, assuming 85 percent inflow to the public sewerage system. If treated wastewater effluent is used in carefully controlled irrigation at an application rate of 5 000 m3/hectares/year, 6 000 hectares could be irrigated.

In addition to the economic benefit of the water, the fertilizer value of the effluent is important. Typical concentrations of nutrients in treated wastewater effluent from conventional sewage treatment processes are as follows: 50 mg/litre of nitrogen; 10 mg/litre of phosphorous; and 30 mg/litre of potassium. Assuming an application rate of 5 000 m^3/hectares/year, the fertilizer contribution of this effluent would be 250 kg/hectares/year of nitrogen, 50 kg/hectares/year of phosphorous and 150 kg/hectares/year of potassium. Thus, the effluent would supply all of the nitrogen and much of the phosphorus and potassium normally required for agricultural crop production. Other valuable micronutrients and the organic matter contained in the effluent would also provide benefits.

Source: FAO, 1992.

Numerous studies have shown that the use of wastewater for irrigation increases crop yields, but good irrigation practices are essential. They are particularly critical to prevent pathogen transmission, the build-up of trace elements and salinity. Wastewater may contain boron from household detergents but certain crops (such as citrus trees) cannot grow where the water contains even low concentrations of boron. Furthermore, heavy metals may accumulate in wastewater-irrigated soils and must be monitored. Certain metals have varying degrees of synergistic and antagonistic effects on plants, which have different degrees of tolerance.

Wastewater can help ameliorate the groundwater crisis, which has manifested itself in falling groundwater tables, seawater intrusion and polluted aquifers. Use of wastewater instead of groundwater can reduce the stress on groundwater stocks by providing a suitable alternative and allowing natural recharge of groundwater resources. Groundwater replenishes slowly, and so artificial recharge with treated wastewater has become progressively more important as a means of boosting the natural supply of groundwater aquifers. When water in coastal aquifers is pumped out at excessive rates, salt water from the ocean or sea may flow into the aquifer and replace the extracted freshwater. Treated wastewater may act as a barrier to saline intrusion when it is pumped back into the aquifer, thus preventing the water from becoming brackish and preserving its value for food production.

Artificial recharge of groundwater can be direct or indirect. The former involves injection of treated wastewater into an aquifer via injection wells, whilst the latter relies on spreading of surface water on land so that the water infiltrates through the vadose zone (the unsaturated layer above the water table). The vadose zone acts as a filter, treating water as it passes through the soil until it arrives in the aquifer. Although artificial recharge with wastewater is recognized as a sustainable groundwater management tool, associated health risks must be carefully evaluated and managed especially in groundwater basins used for domestic water supplies.

3.2. Social issues

As competition for scarce water resources becomes more acute, the social issues of wastewater use become more important. Wastewater may be the only water resource available to poor or subsistence-level farmers living in urban and peri-urban areas. Access to wastewater for agriculture helps many poor families meet their nutritional needs at lower cost (see Box 8.3). For example, in the Guanajuato River basin in Mexico, 140 hectares of land are irrigated with raw wastewater from the city of Guanajuato (Scott *et al.*, 2000). The estimated value of the city's wastewater is US$ 252 000, plus US$ 18 900 for the nutrient and soil amenity value to farmers. The wastewater used by the farmers in this irrigation scheme is estimated to provide US$ 135 worth of nutrients per hectare per year. For poor farmers, this is a substantial amount of money that might otherwise have been spent on fertilizer.

Wastewater use can have different social perceptions depending on the context, and this can affect implementation of wastewater management activities. The local context should be considered carefully in determining risk reduction and risk management measures in wastewater use for agriculture. Cultural values with respect to wastewater will differ widely and will affect the design, implementation and success of government regulation.

Box 8.3 - Wastewater Use in Hyderabad: Food Security and Livelihoods

Wastewater from the cities of Hyderabad and Secunderabad in India flows into the Musi River. During the dry season, 100 percent of the flow of the river is sewage from the cities. Due to population growth and over-pumping of the aquifers, wastewater is often the only source of water for irrigation, used to irrigate an estimated 40 600 hectares of cropland. The wastewater is available year-round and allows the cultivation of up to three crops per year. Over 95 percent of the irrigated land is devoted to growing a forage grass – pará grass or *panicum purpurascens* – which is used to feed water buffalo. One hectare of pará grass brings in more money than an equivalent amount of any other crop – e.g. an average of 2 812 euros per hectare per year compared to 833 euros per hectare per year for leafy vegetables. It is estimated that 40 000 people depend, directly or indirectly, on the cultivation of pará grass for their livelihoods.

Most households with livestock in the urban and peri-urban areas use wastewater-irrigated pará grass as fodder and earn income through the sale of milk. Typically, assuming a six-member household owning one buffalo, 25 percent of the milk produced is retained for household consumption and 75 percent sold. In the rural areas, wastewater-irrigated paddy contributes to almost 43 percent of household food consumption. Many of the urban farmers also grow green vegetables and certain fruits, such as lemons, mangoes, coconuts and custard apples, which they retain for household consumption.

Source: Buechler and Devi, 2003.

Stakeholders are generally more supportive of use of wastewater if they are able to identify and understand the benefits of doing so, the problems the project intends to address and the urgency or need for the change. It will be important to demonstrate that a viable future is dependent on conserving water and preventing groundwater over-exploitation. For stakeholders to have confidence they must be assured that wastewater will be used in accordance with strict public health, agriculture and safety regulations, and will need to be informed of the high level of controls and testing of reused water at various stages of the service chain.

3.3. Potential health effects

The use of wastewater in irrigation has both negative and positive health implications. Domestic wastewater contains a wide range of pathogens that can survive in the environment long enough to be transmitted to humans through water and food consumption (see Table 8.3). Irrigation with inadequately treated wastewater has been linked to disease outbreaks and may also be responsible for some proportion of faecal-oral disease endemic in some countries. On the other hand, the use of wastewater in agriculture may have benefits which are often overlooked or poorly characterized. The risks and benefits of wastewater use are described below.

Table 8.3 - Survival of Various Organisms in Selected Environmental Media at 20–30°C

Organism	Freshwater	Crops	Soil
		(time of organism survival in days unless otherwise indicated)	
Viruses*	< 120, usually < 50	< 60, usually < 15	< 100, usually < 20
Salmonella	< 60, usually < 30	< 30, usually < 15	< 70, usually < 20
V. cholerae	no data	< 5, usually < 2	< 20, usually < 10
E. histolytica cysts	< 30, usually < 15	< 10, usually < 2	< 20, usually < 10
Ascaris eggs	years	< 60, usually < 30	years
Tapeworm eggs	months	< 60, usually < 30	months

* Poliovirus, echovirus and coxsackievirus

Source: WHO, 2006.

3.3.1. Adverse impacts

Domestic wastewater. Poor management of human excreta, including partially treated or untreated wastewater, contributes to the spread of faecal/oral pathogens through contaminated food, drinking water and recreational water. Nearly 6 percent of the total disease burden, or 84 million life years lost per year (expressed as DALYs (disability adjusted life years)), has been attributed to water- and sanitation-related diseases (Prüss *et al.*, 2002). For example, as described in Chapter 6, an estimated 1.6 million persons die every year from diarrhoeal diseases and 5.4 billion cases of diarrhoea every year are attributable to poor water, sanitation and hygiene (Hutton and Haller, 2004).

The use of inadequately treated wastewater for irrigation is associated with a number of infectious diseases. Intestinal worms are the highest risk, along with other pathogens linked to excreta (WHO, 2006). Viruses and protozoa may also be spread from contaminated water to food. Pathogens on produce may remain infectious for long periods of time and cause disease outbreaks far from where the agricultural products were grown. In addition to disease outbreaks, contaminated water and poor hygiene contribute to endemic diseases.

As discussed in Chapter 6, although the nutrients in wastewater can be a valuable resource when used to grow crops, excessive quantities can have harmful effects. If excessive nutrients are introduced into water resources, oxygen is depleted and organisms that require oxygen (such as fish and plants) may not survive. Excessive nutrients can also facilitate the growth of algae, which are in some cases toxin-producing. When ingested or inhaled or when they come in contact with the skin, some of the toxins from such algae may adversely affect human health (Chorus and Bartram, 1999). Toxin-producing algal blooms also adversely affect fish populations.

Industrial wastewater. In many countries, industrial wastewater is mixed with municipal wastewater and used for irrigation. The use of industrial wastewater poses health risks associated with human exposure to toxic chemicals, although the risks are less well understood than those linked to microbial pathogens (WHO, 2006). Industrial wastes may contain toxic organic and inorganic chemicals that can be taken up by crops. The amount of chemicals taken up depend on the types of chemicals and the properties of the soil, and the health effects will vary depending on the type and amount of exposure to the chemical in question (WHO, 2006).

To minimize adverse health and environmental effects, industrial wastewater should either be treated as a separate waste stream from domestic wastewater or adequately pre-treated to remove toxic substances before discharge to municipal sewerage. An important task for regulators is to identify sources of industrial discharges. Governments may then require identified polluters to clean up their wastes (or to divert them from the municipal waste stream). Alternatively, policy may require that all industrial discharges be treated separately from domestic wastewater.

3.3.2. Positive impacts

When used safely for irrigation, wastewater can contribute to human health by increasing food production and household income. By improving the ability to produce sufficient quantities of nutritious food (through cultivation or purchase), use of wastewater can have a beneficial impact on health at the individual and community levels by reducing malnutrition. Malnutrition affects approximately 800 million people (20 percent of all people) in the developing world (WHO, 2000b) and leads to both stunted physical growth and impaired cognitive development. It can also have long-term effects on the health and social development of a community. In one study, children aged 9 who had suffered severe stunting in the second year of life scored 10 points lower on a standardized intelligence test than children who had not suffered from stunting (Berkman *et al.*, 2002).

In some cases, improving the living standards of the poor through irrigation development may lead to better health even when the irrigation leads to some increase in disease vectors (Van der Hoek *et al.*, 2001). For example, where a rice irrigation scheme had been developed in a village in Tanzania, a study showed that even though the irrigation village had more malaria vectors than a nearby savannah village, there was a lower level of malaria transmission in the irrigation village (Ijumba, 1997). This was because the village with the irrigation scheme had more resources to buy food; children had a better nutritional status; and the villagers were more likely to buy and use mosquito nets (Ijumba, 1997).

Irrigation with wastewater can also reduce environmental pollution. Wastewater that is used for irrigation will undergo some natural purification as it travels through the soil, ultimately reducing the amount of pollution that enters surface water or groundwater.

3.4. Health-based targets and risk reduction measures

Human pathogens in fields or ponds do not necessarily represent a health risk if appropriate health protection measures are taken. Health protection measures may either prevent pathogens from reaching the worker or the crop, or they may prevent any pathogens on the crop from affecting the consumer (WHO, 2006).

In developing countries, the level of wastewater treatment is typically low, with Sub-Saharan Africa treating less than 1 percent of wastewater generated (UNICEF, 2000). Although the long-term goal is to move from the unregulated use of untreated wastewater to the regulated use of treated wastewater, the medium term strategy in many developing countries is to prioritize affordable and easily adoptable risk management strategies (IWMI & GWP, 2006). Costs are likely to be low in comparison with the construction, operation and maintenance of conventional wastewater treatment plants.

The 2006 WHO guidelines for safe use of wastewater (2006) apply risk management approaches under the Stockholm Framework and recommend defining realistic health-based targets and assessing and managing risks – along the continuum from wastewater generation to consumption of produce cultivated with wastewater – to achieve these targets. This allows for a regulatory and monitoring system in line with socio-economic realities of the country or locality. In line with those realities, a variety of measures are feasible for health protection: (a) wastewater treatment, (b) crop restriction (restricting wastewater use to certain crops), (c) irrigation technique and wastewater application method and (d) human exposure control.

Although in some cases one health protection measure will suffice to achieve health-based targets, it will often be desirable to apply a combination of several methods at the same time (WHO, 2006). For example, although crop restriction may be sufficient to protect consumers, additional measures are needed to protect agricultural workers. The availability and efficacy of the measures will depend on the local circumstances which must be carefully considered before any option is put into practice (WHO, 2006). It is especially important to consider vulnerable groups. Partial treatment to a less demanding standard may be sufficient if combined with other risk reduction measures to achieve the desired health target.

Health protection measures must use available resources to progressively improve the situation based on risk assessment and risk management (WHO, 2006). Flexibility is important so that measures that are initially effective and cost-efficient can be phased out in favour of other measures as new needs arise (WHO, 2006). Whatever the coverage or time scale involved, implementation should be closely monitored to ensure that the safety measures are achievable, that the health protection measures are functioning as designed and to rectify any mistakes before human contact or consumption results in illness (WHO, 2006).

3.4.1. Wastewater treatment

Several wastewater treatment options are available, including both low- and high-technology processes. Low-technology processes are favoured in most developing countries not only due to lower cost but also simpler operation and maintenance. They can offer a significant reduction in pathogens (FAO, 2009b). Two such options include wastewater stabilization ponds and wastewater storage and treatment reservoirs. Stabilization ponds, which are most effective in warm climates, are the least expensive option and are the easiest to operate and maintain. They hold waste in shallow basins and rely on sunlight, temperature, sedimentation and biodegradation to treat the wastewater. Sedimentation removes protozoan cysts and helminth eggs which remain in the pond sludge. Viruses are removed by adsorption onto solids such as algae. If they settle, the viruses also remain in the pond sludge. Pathogenic bacteria are inactivated by high temperatures, high pH levels or high levels of sunlight or settle into sludge (FAO, 2009b; WHO, 2006).

In Ghana, as in many other countries in West Africa, shallow dugout ponds usually less than 1 m deep and 4 m wide are widely used in irrigated urban vegetable farming sites. In most cases, they are used as storage reservoirs where surface runoff and wastewater effluents are channelled. Other variations include the use of mobile drums and other reservoirs, which are common in areas where irrigation water sources are distant from farm sites. During the storage of water and its gradual use in irrigation, sedimentation takes place and is very effective at removing helminths (i.e. reduced to less than 1 egg per litre) when sedimentation is allowed for 2–3 days, and this improves the irrigation water quality (FAO, 2009b). Many developing countries employ additional low-cost measures to enhance sedimentation or to enhance pathogen die-off (FAO, 2009b).

High-technology processes usually involve engineered systems with relatively higher flow rates and lower retention times. The primary treatment step settles solids in a tank where the wastewater is held for two to six hours; this treatment may also be chemically enhanced. The secondary treatment allows for biological treatment of organic substances with liquid and solid separation. If necessary, a tertiary treatment step may be used to remove any specific contaminants, followed by disinfection. Dual membrane (micro-filtration and reverse osmosis) tertiary treatment has been considered to obtain the highest quality recycled water (EC, 2006). Although expensive, it is suitable for high-value cash crops and is used prior to groundwater recharge.

The downside of these processes is that they require initial capital for the complex infrastructure, which is expensive to build and maintain. Furthermore, the more advanced processes remove nutrients that may be useful for agriculture, including nitrogen, phosphorous and organic matter (FAO, 2009b; WHO, 2006). Some treatment processes may have limited efficiencies in removing pathogens of potential health concern.

Wastewater is generally treated to be fit for the prospective use. The choice of treatment will depend on a range of factors such as the potential for human contact with the irrigated water and the end use of the crop (such as whether it is eaten raw or cooked, peeled or unpeeled and used for fodder or industry). Cost will also be an issue.

3.4.2. Crop restriction and crop selection

Crop restriction consists of restricting wastewater irrigation to certain types of crops, such as non-food crops (biofuel and industrial crops, e.g. cotton), crops that have to be processed before consumption or crops that have to be cooked. However, crop restriction is not an adequate control measure on its own. To protect farm workers as well as consumers, crop restriction should be complemented by other measures such as partial wastewater treatment, controlled application of the wastewater or human exposure control (Mara and Cairncross, 1989).

Crop restriction is relatively simple to implement but is only practical under certain conditions. In particular, it is easier to enforce crop restrictions on a small number of bodies (such as private firms, cooperatives, state farms, water user associations in irrigation districts, or municipal authorities) than on a large number of small farmers. If there is no local experience in crop restriction, its feasibility should be tested in a trial area before being implemented on a wide scale. The trial should also include measures that provide a clear initial estimate of the resources required for enforcement, as well as clarifying the most suitable institutional arrangements for implementation.

Crop restrictions can be hard to implement if necessary conditions such as law enforcement, market pressure and demand for clean produce are not in place. So although there have been successful crop restriction schemes in Chile, India, Mexico and Peru (Buechler and Devi, 2003; Blumenthal *et al.*, 2000b), this has not been possible in other countries where wastewater irrigation is more informal (Scott *et al.*, 2004).

Crop selection can reduce human health risks as some crops are more prone to contamination from pathogens, salinity and toxicity than others. For example, some crops (e.g. low-growing plants and tubers) are more prone to pathogen contamination because their edible parts are more exposed to contaminated soils and irrigation water. In view of reports of food safety outbreaks, the Committee on Food Hygiene of the FAO-WHO Codex Alimentarius Commission convened a meeting of experts in 2007 to provide scientific advice regarding potential public health and trade concerns related to fresh produce. The expert group identified leafy vegetables and herbs as raising the most concern (Codex, 2009). With outbreaks persisting in 2008 and 2009, FAO and WHO began collecting information from national food safety authorities in order to continue refining the risk-based criteria, the list of fresh produce commodities of concern and their relative priority (Codex, 2009).

3.4.3. Wastewater application methods

Because of the potential health and environmental effects of wastewater use, careful application methods are required. Farmers may need encouragement and help to change their irrigation methods, and agricultural extension services can provide that assistance.

Irrigation water, including treated wastewater, can be applied to the land in several ways: by flooding (border irrigation), which wets almost all the land surface; by furrows, which wet only part of the ground surface; by sprinklers, which wet the soil in much the same way that rain does; by sub-surface irrigation, which wets the surface little, if at all, but which saturates the sub-soil; by localized (trickle, drip or bubbler) irrigation, which applies water to each individual plant at an adjustable rate; or by sub-surface partial rootzone drying irrigation, which wets part of the root system whilst the other part is dry or drying (and alternates the two parts).

Certain application methods are safer and more efficient than others. Flooding may be the easiest and least costly, but it also carries the greatest potential health risks. Farmers may have to change existing wastewater irrigation methods to reduce risks. However, implementation of alternative methods will require additional work and expense. For example, to implement furrow irrigation, farmers may need help levelling the land or contour ploughing to create the furrows.

Other irrigation methods may be more efficient, particularly when limited quantities of water are available. However, sprinkler irrigation demands careful measures to protect the workforce and nearby residents from exposure to infectious agents. On the other hand, since sprinkler irrigation is most often practised in large, centralized schemes run by a single body, these producers or institutions are in a relatively good position to ensure that protective measures are implemented (Mara and Cairncross, 1989).

Sub-surface or localized irrigation can often protect best against contamination, use water more efficiently and produce higher yields. These methods are expensive, however, and reliable wastewater treatment is required to prevent clogging the small holes (emitters) through which water is slowly released into the soil (although this is not a problem when bubbler irrigation is the method used) (Mara and Cairncross, 1989).

The timing of wastewater application may help minimize negative impacts. For example, applications may be timed and combined with other application and exposure control methods to facilitate the die-off of pathogens. The amount of time necessary depends on the climate, because pathogens die off more rapidly when the weather is hot and dry and more slowly in cool or wet weather (WHO, 2006). One of the most widely documented field water management measures is cessation of irrigation a few days before crops are harvested to allow for pathogen die-off due to exposure to unfavourable weather conditions such as sunlight (Shuval *et al.*, 1986). As much as 99 percent reduction in detectable viruses has been reported after two days' exposure to sunlight (Feigin *et al.*, 1991). In such systems, regulations require a suitable interval between irrigation and crop handling (Feigin *et al.*, 1991).

3.4.4. Human exposure control

The major challenge for wastewater use is to minimize the risk to human health. Four groups of people are at particular risk from the agricultural use of wastewater: agricultural field workers and their families; those living near the affected fields; crop and meat handlers; and consumers of crops, meat and milk.

In many countries, existing legislation governing occupational health requires employers to protect agricultural workers from exposure to diseases. Employers may need to be made aware of these laws and may need guidance on the protection measures they must take, such as issuing protective clothing (e.g. special footwear and gloves) to farm workers. Concurrent efforts must convince employees to wear this protective gear.

Workers and their families are most likely to live close to agricultural fields and thus local communities are exposed to disease in several ways. They may use contaminated water for drinking or domestic uses, and children may play in contaminated water (WHO, 2006). Extensive irrigation may also lead to increased vector populations and increased risk of vector-borne diseases. It may be necessary to establish physical barriers preventing access to raw wastewater-irrigated fields. Providing safe recreational and bathing water may also be considered (WHO, 2006).

Exposure control fits into a general programme for occupational health when dealing with agricultural employees who work for a limited, identifiable number of employers. It is more difficult to implement exposure control measures for petty traders who sell or make products from the crops produced through wastewater irrigation, unless they can all be found at markets, which are subject to public health inspection. Market inspections may also be good opportunities to advise consumers about the hygienic precautions they should take with the food they purchase to protect themselves from exposure to infection.

Food hygiene should be included in health education campaigns. Consumers should be taught food washing or preparation techniques that reduce pathogen transmission. Crops that are eaten raw as well as crops with hairy, sticky or rough surfaces are more likely to contain pathogens. Certain techniques, such as vigorous washing in a disinfectant or detergent solution or peeling fruits and root vegetables, can significantly reduce contact with pathogens (WHO, 2006). Risks to consumers can be further reduced by thoroughly cooking vegetables and meat, boiling milk and maintaining high standards of personal and kitchen hygiene (Mara and Cairncross, 1989).

Measures to protect human health include providing adequate water supply and sanitation and encouraging hygienic behaviours such as hand washing. Controlling the exposure of workers to faecal contamination in the fields may have little effect if they are exposed to infection from their drinking water and in their home environment. Care must be taken to ensure that the use of wastewater does not contaminate nearby wells or other sources of drinking water.

3.5. Available legal and regulatory controls

Wastewater use for crop production, although common in certain regions, may not be officially recognized or regulated by health authorities. Experience in many developing countries has shown that simply banning wastewater use in irrigation has little effect either on the level of public health risk or on the prevalence of use. This is unlikely to change since the amount of wastewater generated and used will continue to expand along with increasing urbanization. Banning wastewater use is not only unlikely to stop it but may also make supervision and control more difficult. A better approach is to acknowledge that such practices are occurring and support education and promotion on good irrigation practice and health and food safety awareness.

Safe wastewater use requires a strong regulatory framework to maximize the benefits of its use in light of environmental and health risks. The legislative framework should be accompanied by supportive regulatory measures, incentives, coordinated oversight and enforcement.

Legislation

Legislation for wastewater often goes beyond the purview of basic water resource legislation. Certain provisions related to irrigation may fall within a basic water law, whilst provisions related to health will be found within other legislation, such as for drinking water or for occupational safety. At a minimum, governments must ensure that the legislative framework contains essential provisions on irrigation and wastewater and has few overlaps or gaps.

Some jurisdictions enact specific legislation that covers the full range of issues relevant to wastewater treatment and use. The legislation defines and clarifies the responsibilities and roles of state agencies with respect to wastewater, including mechanisms for coordination. In addition, as with other areas of water resource law, the legislation specifies rights of access to and ownership of wastewater, including related land tenure issues. Provisions on environmental protection will also be important. Finally, wastewater legislation must be harmonized with legislative provisions on health, particularly with respect to water quality, occupational health and food safety (WHO, 2006). These principal features of legislation on wastewater are discussed in detail below.

Agency roles and responsibilities

Wastewater legislation touches on both health and environmental issues and thus implicates a wide range of state agencies, including ministries responsible for health, agriculture, education, environment and water resources. Legislation addressing wastewater use must specifically designate which agency is responsible for each area of regulation. In addition, legislation may set up a body to coordinate all agencies involved (WHO, 2006).

Local governments and organizations may also have a role in wastewater use, especially if they are charged with issuing permits and monitoring compliance with wastewater rules or carrying out food inspections at markets. In countries that have decentralized or devolved water management, legislation must establish the division of responsibilities between national and local authorities in wastewater use.

Access rights

As explained in earlier chapters, granting permits or licences and access rights provides farmers or other water users with an important sense of security. This security is particularly crucial for wastewater irrigation practices, as farmers may not develop infrastructure necessary to safely use wastewater unless they are assured of a continued right of access (WHO, 2006). Access rights may be regulated through issuing wastewater use and discharge permits.

Environmental and health provisions

Specific provisions to avoid environmental degradation are necessary. For example, in areas where flooding with wastewater is practised, legislation must provide for measures to avert or minimize harm to nearby water sources, which may be affected by runoff from agricultural fields. Measures may include requiring natural barriers between agricultural fields and water sources or restricting the use of wastewater in sensitive areas or at critical times.

Provisions to avoid environmental degradation may also be necessary where the cost of treating wastewater to limit the salt content is too high. Legislation can control the amount of salt entering the wastewater stream at the point of generation. Egypt, for example, has had success limiting the salt content in its wastewater by regulating the contents of domestic detergents and industrial effluents (WHO, 2006).

Some health issues resulting from wastewater use may best be dealt with in legislation dealing with health and worker safety. Health provisions should set forth requirements for inspections of crops and food products made from crops irrigated with wastewater to ensure that they are safe and to ensure the safety of the workers preparing or selling the food products. Laws may mandate that safety inspections may occur at the field level, the manufacturing level or the market level. As already noted, employers may be required to ensure farm worker safety by providing protective clothing and equipment or taking necessary health protection measures for workers dealing with wastewater. Finally, governments may need to conduct a health impact assessment (HIA) before creating a wastewater use system. (see Chapter 3.)

Regulations, guidelines and standards

In certain contexts, implementation and enforcement of regulations may be difficult, particularly in view of resource, capacity and financial constraints. It is therefore critical that new regulations plan and provide for the institutions, staff and resources necessary to ensuring that the rules are fully adhered to. Regulations should be realistic and achievable in the context in which they will be applied.

Implementation of guidelines for safe use of wastewater will best protect public health when integrated into a comprehensive public health programme that includes other sanitary measures, including personal and domestic hygiene education, outreach and behavioural change. Farmer field schools can impart information about good agriculture and irrigation practices and hygiene.

Specific scientific requirements should be based on guidelines and standards such as those elaborated by WHO and FAO. In setting standards at national level, local circumstances should be taken into account so that realistic targets can be set and achieved. Incremental progress is to be expected.

Microbial standards

Different microbial standards for wastewater use in agriculture have been developed worldwide. Based on an approach that used empirical epidemiological studies, microbiological studies of the transmission of pathogens and quantitative microbial risk assessment, WHO created guidelines for safe use of wastewater in agriculture (Blumenthal *et al.*, 2000; WHO, 2006). These should form the basis for regulations dealing with wastewater use.

Chemical standards

As discussed earlier, industrial wastewater is often mixed with municipal wastewater, which is then used for irrigation. The health risks associated with chemicals found in wastewater and sludge must be given more attention, particularly as industrialization increases in developing countries. WHO has developed standards for a selection of harmful chemicals that might be found in wastewater (WHO, 2006). In many situations, the safety of the wastewater for irrigation will need to be determined on a case-by-case basis, depending on the type of chemicals suspected to be present. Chemical analysis of the wastewater may be necessary.

IV. CONCLUSION

Agriculture is the chief user of water resources worldwide, and there is little doubt that the use of wastewater for irrigation will be important in meeting the world's rising food needs. The use of wastewater can help redress growing water scarcity and improve food production but it requires a comprehensive regulatory framework to maximize the benefits of its use whilst taking into account human health and the environment. Wastewater irrigation must be governed by a legislative framework underpinned by science-based guidelines, accompanied by effective risk management and implemented in tandem with public education campaigns.

As a final note, law-makers should recognize that in some cases, imposition of overly strict water quality standards for wastewater could paradoxically lead to the use of water that is less safe. In countries with inadequate resources for wastewater treatment or enforcement, farmers and producers may simply ignore standards that they are not physically or financially able to comply with. Realistic guidelines should be adopted that match the social, economic and environmental conditions of each jurisdiction.

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9

INTEGRATED MANAGEMENT OF WATER FOR HUMAN AND ECOSYSTEM NEEDS*

Contents

* This chapter was prepared by Bruce Aylward and Christie Popp.

As outlined in earlier chapters, human development has depended on a variety of consumptive and non-consumptive uses of water, some of which have caused adverse effects on ecosystems through alterations to the natural water cycle. These alterations have, however, allowed the provision of welfare-enhancing services to society. A critical challenge is therefore the need to strike a balance between the use of water for human development and the use of water for ecosystem management.

This chapter introduces the concept of ecosystem uses of water alongside human uses. Governments have traditionally dealt with ecosystems by regulating water use, setting quality standards and defining maximum limits for polluting agents. The broad objective has been to maximize human benefits whilst respecting certain constraints related to the degradation of ecosystems and the protection of human health. By contrast, integrated water resource management embraces a more holistic approach to water, recognizing its myriad facets and uses, managing water at the watershed level and taking into consideration both groundwater and surface water and the interconnections between them.

This chapter begins with a review of conventional water resources management – of watersheds, groundwater and surface water – and the concomitant misallocation, overuse and pollution of water resources. It then discusses how to create an enabling environment for a more holistic management model. The last section outlines available regulatory and market mechanisms that can induce changes in users' and polluters' behaviour so as to increase the productivity of water across the full range of human and ecosystem uses.

I. WATER RESOURCE MANAGEMENT

Water management has traditionally focused on single water uses without considering the impact of management decisions on the water cycle as a whole and therefore on other legitimate uses. The lack of a wider lens has led to conflicts between users and to deterioration of freshwater sources at the watershed, groundwater and surface water levels. The next sections examine elements of water management, including watershed management, groundwater management and surface water management.

1.1. Watershed management

Watershed management covers both water resources and land use management, recognizing that land use has an impact on the water cycle and on downstream water quantity and quality. For example, the harvesting of timber resources will affect the quantity and timing of downstream water yield and may lead to erosion and downstream water quality problems (Bruijnzeel and Critchley, 1994). On the other hand, restoration or protection of wildlife may increase the risk to municipal water supplies from biological pathogens such as giardia and cryptosporidium, which are carried by wild animals (NRC, 2000).

In a watershed, land management upstream is linked to human welfare and ecosystem function downstream. Land use and land use management affect the water cycle in several ways but principally by altering the vegetation cover and thus changing the properties of the soil. This affects a variety of hydrological functions including (a) precipitation; (b) annual water yield; (c) seasonal flows, particularly baseflow; (d) groundwater recharge; (e) storm flow response or flood flows; and (f) runoff and leaching of chemical and biological pollutants. Good watershed management means ensuring that changes in downstream (off-site) hydrological services are included in the decision-making process of the land manager, along with the costs and benefits of the on-site hydrological services.

Public agencies or councils may adopt watershed management by introducing incentives to promote, amongst private land owners, land and water management measures that preserve the ecosystem of a given watershed. Upstream land managers are usually concerned about soil erosion to the extent that it affects on-site productivity of the land. Too much erosion may indeed lower plant yields, giving the land manager an incentive to invest in soil conservation measures. However, a private land manager will never pursue the minimum possible erosion rate but rather define an acceptable rate of erosion that is consistent with maximizing long-term profit from the land (McConnell, 1983).

Although the erosion produced upstream travels downstream as suspended sediment (thereby decreasing downstream water quality and increasing water treatment costs), there is no incentive for the upstream land manager to reduce this economic impact. The behaviour will continue until the land manager is either forced to adhere to some other standard or technology or is provided with some positive or negative incentive that encourages a reduction in the erosion rate. Watershed management in this case may include the identification of new incentives for the upstream land manager in order to ensure both on-site productivity and lower water treatment costs downstream.

1.1.1. Land use and downstream hydrological change

Land use and land use management practices may alter (a) the quantity of precipitation that is intercepted and evaporated from surfaces (particularly vegetation but also soil); (b) the quantity of water that is transpired and evaporated by plants; (c) the rate at which water infiltrates the soil and hence the level of surface runoff; and (d) the runoff or leaching of materials, nutrients and pathogens into groundwater and surface water. These land and water interactions can be complex.

In many locations, the actual changes in flow, quality and timing are difficult to predict or ascertain with any degree of certainty, but generally, removal of natural vegetation and disturbance of soil will worsen water quality (Bruijnzeel, 2004). For water quantity, the causal relationships are not as well understood. The effects of land use and vegetation on water quantity are currently being debated by scientists and disagreement is widespread (see Box 9.1). Many scientists suggest that vegetation cover with high rates of interception and transpiration (such as certain forests and crops) evapotranspires (or consumes) more water than other types of land cover. This means that the annual water yield may actually increase under a different land use because of increased water runoff and a possible increase in water infiltration into the soil.

However, it is important to consider not only the total water flow but also the possible alterations in the minimum flow rates during dry periods and in the maximum flooding rates during wet periods. A change in those peaks of water availability may have a greater downstream impact than an increase in the annual water yield. In this regard, a land use change involving deforestation may result in soil compaction, which in turn would reduce the water infiltration rate and subsequent groundwater recharge. This could result in a reduced dry season baseflow. But even in this case, scientific evidence suggests that as long as the deficit in groundwater recharge does not exceed the increase in the annual water yield caused by reduced evapotranspiration, even drastic land use changes such as forest to pasture may lead to a higher dry season baseflow.

Box 9.1 - Conflicting Views: Water Yield, Groundwater Recharge, Seasonal Flows and the "Sponge" Effect

When human activities reduce the vegetation cover (e.g. by deforestation), the rate of evapotranspiration is also reduced. This is the case in both temperate and tropical regions (Bosch and Hewlett, 1982; Bruijnzeel, 2004), but it goes against the popular perception that forest areas "produce" more water than non-forest areas. Although it is true that forests naturally grow where there is more precipitation, it is precipitation that causes forest and not the other way around. Forest areas might actually "collect" more water than neighbouring non-forest areas but they deliver less due to their higher evapotranspiration rates. In this regard, the scientific community is fairly unanimous in stating that more water runs off and infiltrates into the ground in areas with lower evapotranspiration (Bosch and Hewlett, 1982).

Human alterations of natural vegetation have a less clear-cut impact on seasonal flows, particularly on dry season baseflow. Theoretically, lower levels of evapotranspiration following vegetation removal can cause dry season baseflow to rise because of a higher water runoff and possibly a high infiltration rate. However, this response may be reduced or even reversed if soils are so compacted by the subsequent land use that infiltration of precipitation is significantly curtailed (i.e. a reduction in the so-called "sponge" effect). Most scientific observation to date reveals that more often than not the removal of forest leads to a fall in dry season baseflow (Bruijnzeel, 2004).

Although this conclusion seems to confirm the existence of the "sponge" effect of forest cover, current scientific understanding of forest hydrology argues against reliance on this effect as a basis for management and policy decisions (Aylward, 2005). Furthermore, research has shown that the hydrological impact of land use changes is caused not only by the initial intervention but also by the subsequent type of land use and the management regime applied (Bruijnzeel, 2004). Hence, the popular perception that the alteration or removal of natural vegetation automatically leads to reduced water availability and lower dry season flows should not be overstated.

1.1.2. Precipitation and rainwater harvesting

Rainwater harvesting is the act of trapping precipitation for future use in domestic, farm or other activities. Typically it is implemented at household or commercial-building scale or for industrial purposes. Impermeable surfaces such as tin or other roofing materials are used to collect rainwater, which is funnelled through drainpipes or other means into above- or below-ground storage containers for future use. Other less common examples include the preparation of wind breaks (using natural or human-made materials) to capture fog. Rainwater harvesting is often portrayed as an innovative solution in water management – even a viable alternative to building dams for storage (WCD, 2000).

Where a household adopts a harvesting system in place of direct pumping or withdrawal of water from a water body, this may have no net impact on the water cycle. On the other hand, if the convenience and low operational costs of rainwater harvesting lead users to expand their use and consumption of water, there may be an overall increase in net use and consumption by the household. In this case, rainwater harvesting by an upstream water user may deprive users downstream. On the other hand, in the rare cases where precipitation runs off the land or into an aquifer and has no further human or ecosystem use downstream, rainwater harvesting can be a sustainable option.

1.1.3. Unresolved issues

Whatever the exact hydrological impacts in a specific locale, it is clear that land management actions and rainwater harvesting by upstream land managers, households and industry have the potential to impair access to and quality of water for downstream users. Where downstream hydrological goods and services are in scarce supply, these changes may have important social and economic impacts. In the case of land management, the problem lies in the fact that land use regulations do not require upstream land managers to integrate the downstream impacts of their decisions (or the preferences of downstream users) into the decision-making process. In the case of rainwater harvesting, depending on the national system, in most cases the technique is largely unregulated.

Chapter 5 introduced types of resources and identified land use and rainwater harvesting as a common pool resource. This classification stems from the inexorable pull of gravity, which causes both positive and negative changes in water quantity and quality to move inevitably down-gradient. From the perspective of the upstream land manager, it is difficult to prevent downstream users from enjoying any benefits of action taken to improve land management and consequently water supply and quality. Equally, the downstream user is effectively at the mercy of the upstream land owner. An upstream land manager may capture additional water for household and industrial use or may plant a crop with higher water use requirements, which affects the quantity and quality of prior and profitable downstream uses of water. This is despite the fact that in many situations headwater areas are less productive and the water would have had a higher productive value in downstream uses. Moreover, agricultural activity downstream may be an important livelihood or source of food security for local communities, and downstream users may have made significant investments in infrastructure based on the expectation of continued access to clean and abundant water supplies. It is clear in these cases that the upstream land manager's actions may have a significant social and economic impact on downstream communities.

In this case, location (i.e. upstream vs. downstream) defines the problem. The inability of the downstream community to prevent the upstream land manager from taking certain actions is likely to lead to a less than optimal use of the water resource from a social perspective. It can lead to a first-come, first-served situation, akin to that of an open access fishery, with upstream fishers having the advantage. In this case, as described in Chapter 5, market failure occurs due to the problem of excludability.

Regulation of surface water use is the first step towards conflict resolution. The regulatory framework should provide the means to protect prior consumers of water and users of hydrological services. This may be easiest where water is considered a public good to be managed by the state in the interest of the population. The state grants users permits for the diversion and use of the water, which gives legal certainty and security to the rights and obligations of all riparian users, both upstream and downstream. On the other hand, where the regulatory system was devised to solve the open access problem amongst surface water users, it may not function well in a conflict between surface water users and rainfall users. The upstream users still risk harming the downstream community and imposing net costs on society. Recognition of this problem is only slowly emerging and initial efforts to address it will be reported later in this chapter.

1.2. Groundwater management

Aquifers can be defined by their rate of inflow (from land and surface waters), by the quantity of water held (actual and potential) and by the rate of discharge (to surface waters or the ocean). Where the stock of water held in an aquifer is small relative to the annual inflow and outflow, the aquifer may be considered an underground river. Conversely, when the stock is several times the annual inflow and outflow, the aquifer may be defined as an underground storage reservoir. Aquifers thus have different naturally occurring physical characteristics that present differing management challenges. The next sections examine the features of each type of groundwater system.

1.2.1. Groundwater as a river

Groundwater can be considered an underground river in that the water is routed through the earth and then back out as discharge into surface waters or the sea. This can occur at different time scales. In some headwaters or along a narrow river valley, runoff or surface water may infiltrate into the ground only to appear as surface water a short time and distance further downstream. Alternatively, groundwater recharge in the headwaters of a large basin may take hundreds of years to be pushed through the earth by hydraulic pressure and then appear many miles downstream.

In natural conditions, groundwater is a renewable resource in that each year new precipitation percolates through the ground to become groundwater and groundwater discharges to surface water. Groundwater pumping interrupts this process and can create temporary drawdowns and deficits in this underground flow. In extreme cases, the pumping may suck up the entire underground river and temporarily stop the flow emerging at the point of discharge. Even so, the resource remains renewable since the underground river does not store water.

1.2.2. Groundwater as a reservoir

Considering groundwater an underground reservoir suggests different physical and therefore economic characteristics. In this case, the aquifer does not regularly discharge its waters back to surface waters: it only does so to drain excess water when it is full. Thereafter, until reaching an equilibrium where recharge equals discharge, the annual water recharge will keep filling the reservoir without any return flow to surface waters.

Reservoirs of stored water may have formed in hundreds if not thousands of years where inflow exceeded outflow. In economic terms, the storage in the reservoir represents stored capital. The capital can be maintained when groundwater pumping and any other outflow do not exceed the annual recharge. An alternative policy would allow the capital to be drawn down by generating annual income over time without regard to the regeneration rate of the aquifer. This income would be in addition to that generated by the use of excess natural recharge (i.e. the water flowing out from the full aquifer). In such cases groundwater reservoirs are considered exhaustible resources (like oil reserves) in that a high level of demand for the resource may lead to an extraction rate that ultimately depletes the stored water.

For economists the question of whether or not to exhaust an aquifer and then turn to other supplies has been a question of academic interest (Koundouri, 2004). For others, particularly practitioners, the risk of exhausting the resource is often a catalyst for improved management. Indeed, in an interesting study of Southern California the net benefits of managing the resource and avoiding exhaustion have been shown to be considerable (Blomquist, 1992).

1.2.3. Unresolved issues

Traditional water management has done little to limit groundwater pumping and protect aquifers. This situation has led to several problems:

- over-exploitation of groundwater reservoirs;
- conflict between competing groundwater users (i.e. extraction by one party negatively affecting the other party by drying up their well or lowering the water table);
- reduction in surface water discharge that has led to ecosystem degradation or harm to existing downstream human uses.

The causes of these problems can be traced back to a number of market and policy failures. First, the failure to plan and adequately regulate the off-take from groundwater reservoirs has led to a common pool resource situation. With no ability to exclude others from accessing the reservoir, each user has every incentive to use as much water as fast as possible. Second, the lack of integrated regulation of groundwater and surface water means there is little consideration for the linked impacts. The lack of groundwater regulation can also lead users of regulated surface water to turn to unregulated groundwater as an alternative, with additional negative effects.

Given its status as a renewable resource with elements of exhaustibility, groundwater needs to be managed so as to maximize the benefits in the presence of climate variability. The focus of management has often been on managing the inflow of water and the reservoir function of an aquifer for the purposes of sustainable extraction of groundwater, with much less attention paid to the discharge portion of the relationship. In the Southern California example just noted, for instance, the need to ensure that the reservoir was robust enough to prevent saline intrusion from the ocean was indeed part of management objectives (Blomquist, 1992). But little interest has been shown in ensuring that discharge from aquifers into surface waters supports ecosystem needs and other downstream uses (Glennon, 2002; WWP, 2007).

1.3. Surface water management

The development and use of surface waters over the last few centuries, and in particular in the twentieth century, has modified the hydrological regime and associated inland freshwater ecosystems in four principal ways:

- ecosystem simplification as, for example, in the American West where the eradication of beavers and beaver dams, the channelization and dredging of streams, the draining of wetlands and the removal of riparian vegetation reduced water storage, decreased evapotranspiration and increased the "flashiness" of the hydrograph (i.e. its rising to a high peak after rainfall);
- damming and diversion of waters from creeks, streams and rivers primarily for irrigation purposes but also for domestic, industrial and commercial use, which reduced or dried up the streamflow, increased groundwater recharge rates from canal- and ditch-transmission loss and on-farm inefficiencies and raised evapotranspiration rates on land;
- damming and impoundment of waters in large reservoirs for irrigation, hydropower and flood control, which increased evaporation and groundwater recharge rates at the reservoir sites and also greatly modified the flow regime, in some cases inverting the hydrograph (i.e. reducing streamflow during wet months below the reservoir level as water was stored and then increasing streamflow in dry periods as water was released);

- damming and impoundment of waters in large run-of-river reservoirs for hydropower, which altered the daily and weekly hydrological regime and effectively blocked migration of anadromous fish.

The cumulative impact of all of these changes on the hydrograph and on freshwater ecosystems has been extensive and far-reaching. A study of 227 river basins around the world found that 37 percent were strongly affected by fragmentation and altered flows and another 23 percent were moderately affected (Revenga *et al.*, 2000). The Millennium Ecosystem Assessment expects that 50 percent of inland freshwater habitat was lost in the twentieth century (Finlayson and D'Cruz, 2005).

During the time that these modifications to the hydrograph were taking place, impacts on inland freshwater ecosystems were not a major societal concern. But as the countries that developed their water resources prospered, the impacts multiplied and deepened and today are recognized as major environmental issues. This awareness is a product of both a utilitarian drive to protect and restore these systems for human use and a pure sense of biodiversity and natural heritage stewardship. As more countries grow and develop their water resources, awareness of the potential problems with altering the hydrograph is growing. There is also increasing recognition that some of the modifications (such as species extinction) are irreversible and the costs of after-the-fact ecosystem restoration, even where possible, are large.

The primary market and policy failure is not including environmental flows as a recognized use of water, instead mediating only amongst human uses. Downstream ecosystems that depend on a given surface water flow are accorded no standing nor can they adapt to or alter decisions by upstream water users. Environmental flows have naturally been chipped away at and degraded, leading to the present perilous state. The next sections examine emerging solutions to resolving these and other failures.

II. IMPROVING REGULATORY SYSTEMS

As should be clear from the review just made, the main weakness of most existing regulatory approaches is their failure to include the different types and uses of water in a single framework. Emerging approaches to improving water resource management attempt to include all components of the water cycle. The next three sections explore three ways that jurisdictions have attempted to regulate the whole water cycle: through environmental flows, conjunctive management and exempt uses.

2.1. Environmental flows

Although the term "environmental flow" may be of recent origin, concerns over river health and function have been voiced in many developed countries for over half a century. Still, few countries have incorporated into their legislation provisions for maintaining flows for ecosystems (Dyson *et al.*, 2003). Fewer still have provided the regulatory framework needed to actively restore degraded systems. In many developing countries, management remains focused on such goals as ensuring a supply of water or building infrastructure to meet water demands. Little time or energy has been directed at managing water for the environment's benefit. However, initial efforts are under way in many developing countries to take account of environmental flows, and the following examples should provide useful guidance.

2.1.1. Protecting flows in intact river systems

In the United States of America, instream flows are protected under the Wild and Scenic Rivers Act (WSRA),[1] which protects certain rivers and streams (or portions of rivers and streams) from obstructions that impede the free flow of water. The goal, as the United States Congress declared, is to protect those rivers that "possess outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural or other similar values" (sec. 1271). A river is eligible for protection if it is free-flowing and if it and its adjacent land area possess some of the values mentioned above (e.g. scenic or recreational values) (sec. 1273(b)). In addition, in some circumstances, the river may be eligible if it can be restored to a free-flowing condition.

The WSRA divides eligible rivers into three categories: wild, scenic or recreational. A wild river or stream will generally have to be unpolluted and as close to pristine as possible. It must also not have any impoundments and must be inaccessible except by trail. A scenic river must also be free of impoundments but may be accessible by roads in certain places. For the most part, a scenic river would be primitive, with undeveloped shores. Finally, a recreational river must be easily accessible and might have some shoreline development and a past history of impoundments or diversions (sec. 1273(b)(1)–(3)).

[1] U.S. Code, Title 16, Chapter 28 (as amended, 2008).

The federal government is subject to both prohibitions and obligations under the WSRA. Section 7, for example, prohibits the federal government from licensing new hydroelectric dam projects on the protected rivers. Licences and assistance for other water resource projects are permitted upstream or downstream or on a tributary of the protected river but only where the projects do not "invade" the river area or "unreasonably diminish" its values (sec. 1278). Federal agencies have an obligation to administer "[e]ach component of the national wild and scenic rivers system" so as to "protect and enhance the values which caused it to be included in said system" (sec. 1281). Furthermore, federal agencies must create management plans that address practices that are "necessary or desirable" to achieve the goals of the WSRA (sec. 1274(d)(1)).

Because the federal government shares certain powers with state governments, regulating the free flow of these rivers also requires sharing jurisdiction. In general, federal law controls quantity (i.e. the instream flow) through both the WSRA and the federal reserved rights doctrine, which provides that that when certain federal lands are set aside there is an implicit requirement that they have sufficient water to fulfil the purposes for which they were established. The quantities of water are set either by adjudication or by agreement between the federal and state government.

Because water rights are adjudicated in state courts, however, the utility of a right will vary according to its date of priority relative to other existing state water rights. In the 1908 case establishing the reserved rights doctrine,[2] the U.S. Supreme Court held that although later water users had perfected their water rights under Montana state law, the water rights of Native Americans had priority since the reservation was established earlier in time. In most cases, the WSRA rights will be junior to most irrigation rights across the Western United States. Because the WSRA also requires the federal government to give just compensation to rights-holders if their water rights are taken (sec. 1284(b)), the WSRA mainly serves as a federal restriction limiting future water resource development in relatively intact systems.

2.1.2. Protecting and restoring flows in over-allocated systems

In basins that are highly modified and in dry climates where existing rights to use water often exceed available surface water supplies in normal precipitation

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[2] Winters v. United States, 207 U.S. 564 (1908).

years, efforts to restore stream flow will often rely heavily on policy reform and legislation. First and foremost, legislation should recognize ecosystem uses (i.e. for fisheries, wildlife, recreation and water quality) alongside other uses. This involves setting up the relevant administrative process to allocate permits for such uses and also requires a policy decision on the relative priorities of the new environmental flow rights and existing rights.

By far the simplest way to ensure ecosystem health is to prioritize environmental flows above other uses. The obvious difficulty is that in some cases this may reduce or eliminate existing human uses. The Constitution of South Africa guarantees access to sufficient water and a safe environment as fundamental human rights, contingent on the availability of state resources. South Africa's 1998 Water Act reserves a minimum quantity of water for both human and ecological needs before allocation to other uses (including existing uses established under the 1956 Water Act). In the implementation of the human needs portion of the act, the government now provides a minimal "lifeline" of free water (the "social reserve"), equivalent to half of the minimum standard established by the World Health Organization.

Implementation of the minimum quantity for ecological needs (the "ecological reserve") has awaited the formation of catchment management authorities and the preparation of catchment strategies which include studies of environmental flow requirements. In 15 out of 19 water management areas in the country, the demand from all uses – that is, existing uses plus the expected levels for the social or ecological reserve – exceeds water availability, and the reserve is effectively not being met (Pollard *et al.*, 2007). Commentators suggest that the likelihood of full implementation of the ecological reserve is limited, with some experts acknowledging that as with other rights-based approaches the implementation of the reserve system will be subject to "progressive realization" (du Toit, 2007; Quinn and Marriott, 2006). In 2007, comprehensive reserve determinations commenced in four priority catchments (DWAF, 2007a). The challenge of actually enforcing such determinations against existing uses lies ahead.

The European Union's Water Framework Directive (No. 2000/60/EC) also addresses environmental flows. The directive calls for all states to achieve "good ecological status" in all water bodies by 2015. It does not posit environmental flows as an objective *per se* but rather as a means of achieving the "good ecological status" referred to in the legislation (Acreman and Littlejohn, 2007). There are provisions for exceptions in case of water bodies declared to be heavily modified or for which the costs of compliance are disproportionately high. It remains to be seen how successful this approach will be. In the United Kingdom, initial assessments by environmental flow specialists suggest that compliance with the directive will require major modification of existing water use (Acreman and Littlejohn, 2007). Indeed, using existing methods and data, an initial assessment by the government was unable to even quantify the cutbacks in existing water uses that would be necessary to ensure sufficient instream flows to meet good ecological status (DEFRA, 2007).

In the Western United States, a number of states have passed legislation to establish instream flow as an authorized beneficial use and to allow state agencies to apply for minimum stream flow levels. Unlike the case of South Africa or Europe, however, these instream flow levels are not prioritized relative to existing water uses. Although diversions for irrigation severely curtail flows and result in poor ecological condition, the sociopolitical climate in the agrarian west made any attempt to effectively expropriate existing water rights for instream use a losing proposition. For example, under the U.S. State of Oregon's 1987 Instream Water Rights Act, minimum flows established by state agencies are full-fledged water rights but carry priority dates based on their establishment. They therefore do not serve to restore stream flow but rather serve only to prevent additional allocations when existing rights and instream rights fully account for available streamflow. On the other hand, the 1987 Act made provision for the conversion of existing out-of-stream water rights to instream rights through purchase, lease, donation and conservation. The Act in effect created a market for reallocating existing rights to instream rights with the key proviso that there be no loss of priority when the change to instream was made.

2.1.3. Restoring flows through species protection

An alternative to protecting or restoring rivers or flows directly is to place legal protections on the species that depend on water and flows for their habitat needs. In the United States, the Endangered Species Act of 1973 prohibits federal agencies from authorizing, funding or carrying out actions that would destroy or adversely modify habitat designated as critical for endangered species. Private groups that may "take" species through habitat degradation are also potentially at risk of sanctions under the act. Just as a land owner could be required to halt land development for fear of impacts on an endangered rodent, so could a water right holder be forbidden to divert or use water should such water use impair habitat for an endangered fish.

Perhaps the most illustrative case is the Pacific Northwest salmon, a species found in California, Idaho, Montana, Oregon and Washington in the United States. Since the early 1990s a number of federal agencies involved in hydropower or storage reservoirs for irrigation have been trying to reduce or mitigate their impact on salmon habitats. For example, the Bonneville Power Administration, which produces power on the Columbia River, spares water for the benefit of salmon and funds a Fish, Wildlife and Environment Program that spends more than US$ 150 million a year to improve conditions for Pacific Northwest salmon.

2.2. Conjunctive management

Conjunctive management is another way to regulate the whole water cycle, by considering surface water and groundwater as parts of the same hydrological system. Conjunctive management recognizes that a unit of water that recharges the aquifer, a unit of water in the aquifer and a unit of water that discharges from the aquifer back into stream flow actually represent only one unit of water. True conjunctive management should manage surface waters both upstream and downstream from the aquifer whilst regulating groundwater pumping. It should also consider aquifers as recipients of pollutants and take into account the resulting impacts on the quality of water withdrawn or discharged for human and ecosystem uses.

Conjunctive management has been adopted in Australia, Canada, Israel, South Africa and some states in the United States (UDWR, 2005). Implementation has not been widespread, in part because conjunctive management requires a strong legal system and well-functioning institutional arrangements and in part because many countries lack sufficient information about the linkages between surface water and groundwater. Precise data is needed to accurately project how different management actions will affect hydrological function and water availability. Conjunctive management is also a comparatively recent approach.

Essential legal changes to facilitate conjunctive management fall into two principal areas: water rights and institutional arrangements. In both cases, the key objective is legal certainty. Before agreeing to implement a conjunctive management system, surface water users and groundwater users must be assured that their rights and their investments will be protected.

Water rights. The legal framework should establish secure, well-defined water rights to use and to store specific amounts of surface water and groundwater (Blomquist *et al.*, 2001). Water rights in a conjunctive management system affect incentives: the more defined the water rights, the more incentive rights-holders will have to store water and vice versa. Water rights under a conjunctive management system take the form of licences or permits that specify a certain allocation of water and explicitly state that they are for inter-connected uses. It is also important to recognize the potential for the rights of third parties to be impaired by the implementation of a conjunctive management system (Foley-Gannon, 2000). In the absence of clearly defined rights, legal challenges can prevent or delay implementation, which can be costly (Foley-Gannon, 2000).

Institutional arrangements: Conjunctive management projects often involve multiple organizations or public-private partnerships (Blomquist *et al.*, 2001). This is due in part to prior allocation of authority over surface water and groundwater to various agencies, and also to the often great distances between surface waters, aquifers and downstream discharge zones. This complexity raises transaction costs. Establishing coordinating authorities or associations – water banks, water districts or other special agencies – may lower costs and also pool the risks associated with storing and recovering water (Blomquist *et al.*, 2001).

Conjunctive management arrangements need not take one form (e.g. centralized versus decentralized), but whatever form is adopted, the legislation should clearly outline the scope of agency control and administration. Local entities or agencies should have specific authority to engage in and participate in conjunctive management programmes and to enter into conjunctive management agreements. Legislation should also specify the scope of agency control over stored water. Agencies should be authorized to define rights to native water supplies (the naturally occurring groundwater) and to prioritize rights to available space, to protect recharge areas and to monitor extractions (Foley-Gannon, 2000).

Legislation may also define the extent of agency responsibility for protecting water quality and regulating the export of water (Foley-Gannon, 2000). Legislation may also require agencies to adopt water management plans, which investigate the hydrology of a given water basin, related water quality, supply and demand issues and existing water rights.

2.2.1. Australia

Australia has created perhaps the most comprehensive national plan for conjunctive management. Known as the National Water Initiative (NWI), the plan was signed by the Commonwealth Government of Australia and the governments of Australian Capital Territory, New South Wales, Northern Territory, Queensland, South Australia and Western Australia. Amongst the objectives of the plan are to create a "nationally compatible market, regulatory and planning based system of managing surface and groundwater resources for rural and urban use that optimises economic, social and environmental outcomes by [recognizing] the connectivity between surface and groundwater resources and connected systems managed as a single resource" (NWI, 2004).

Australia has set forth four principles for conjunctive management: (1) physically connected waters should be managed as one; (2) water is assumed to be connected until proven otherwise; (3) all water users – groundwater and surface water – are to be treated equally; (4) and jurisdictional boundaries should not prevent management actions (Fullagar, 2004).

Amongst other features of the plan, states are encouraged to create a single licensing system to improve trade by assuring rights-holders that their rights are secure. Another important element of the plan is the need to coordinate surface water and groundwater use. The plan recognizes that when restrictions are placed on allocations from surface water, water users will turn to groundwater to fulfil their water needs. Thus, states are encouraged to implement "coordinated embargoes", i.e. concomitant restrictions on groundwater use.

Each state or territory is charged with either adopting a legal framework in accordance with the requirements of the NWI or updating any existing legislation that is not in line with those requirements. For example, New South Wales may have to review its Water Management Act of 2000 as it allows water management plans to manage surface water and groundwater separately. Although state policy is to manage water in an integrated way through linkages between plans, many of the links are absent. The Murray-

Darling Basin Groundwater plans, for instance, do not address surface water even though groundwater has an impact on surface water flows.

2.2.2. United States of America

Several states in the United States have enacted conjunctive management laws or programmes of various sorts. These states tend to be in the West and have prior appropriation systems or dual systems of prior appropriation and riparian rights. The existing conjunctive management regimes fall into three general categories: states that manage their groundwater and surface water separately (even if they integrate management in certain districts); states that manage water in two separate systems with integrated permit reviews (i.e. permits are reviewed for their effects on both surface water and groundwater); and states that manage both types of water together, with no legal distinction between them (Tellman, 1996).

California manages its surface water and groundwater in two separate systems, although it encourages conjunctive water management through certain projects and funding. Surface water rights are better defined than groundwater rights, which have developed over time and mostly through judicial decisions and some agency decisions, with little standardization throughout the state. California generally follows the correlative rights doctrine for groundwater management, which means that overlying land owners share an equal right to water and shoulder an equal burden in times of shortage. These rights, unlike other water rights in the Western United States, are not dependent upon use (i.e. they are not forfeited in case of non-use).

Conjunctive management in California is undertaken at the local level by basin organizations driven by local conditions (Blomquist *et al.*, 2001). Because of this decentralized approach, and because the groundwater rights in California are not well defined, users may have little legal assurance that they will be able to recover later the water they store now (Blomquist *et al.*, 2001). Nonetheless, despite the obvious weaknesses, conjunctive management projects continue to be adopted in California (Blomquist *et al.*, 2001).

In the last few years, California's Department of Water Resources has taken additional steps to encourage conjunctive management through its Conjunctive Management Program. The associated water plan has three components: first, when surplus surface water is available, use it to recharge groundwater; second, when surface water is scarce, use the stored groundwater; and third, create monitoring and evaluation programmes to "allow water managers to respond to changes in groundwater, surface water, and environmental conditions that could potentially violate management objectives or harm other users" (DWR, 2005). In addition, the water plan intends to improve water quality, reduce groundwater overdrafts and reduce salt water intrusion along coastal areas.

Colorado, by contrast, uses a prior appropriation system for both surface water and groundwater rights. Because the latter are often junior to the former, most of the groundwater rights cannot be used. This is because pumping would lower the stream flow of the surface water, thereby disrupting senior use rights (Blomquist *et al.*, 2001). Through the state's Conjunctive Management Program, groundwater users can obtain water rights without interfering with the senior surface water rights.

The most commonly used method of conjunctive management in Colorado is "stream augmentation" (Blomquist *et al.*, 2001). Groundwater users acquire surface water, which they give to the State Engineer, who releases the water when the surface water users need it. The amount of water that groundwater users must provide to the State Engineer depends on the amount pumped by their wells. For example, in the Arkansas River Basin, where the well water is used to supplement surface water, the groundwater user need only replace 30 percent of the water pumped. By comparison, if the well water is used for sprinkler irrigation, the groundwater user must replace 7 percent of the pumped water (Blomquist *et al.*, 2001).

Colorado has a well-established water rights system, and water rights priorities are generally identified. Even so, complying with the rules for conjunctive management can be difficult because of the costs and risks involved. For this reason a number of organizations have been established to help administer the system. They help water users, especially small irrigators, deal with compliance and pool their risk (Blomquist *et al.*, 2001).

Utah is another example of conjunctive management in the United States. Most of the water resources in the state are closed or restricted to new appropriations, with only 26 percent of the water resources open to further development (UDWR, 2005). Since the least expensive sources of water have already been developed, conjunctive management has grown in importance. The state began experimenting with conjunctive management in the 1930s and today three conjunctive management projects are in operation (UDWR, 2005).

Utah's system relies on a variety of permits. For example, users intending to recharge groundwater must have a recharge permit and must hold a valid water permit for the water to be recharged. Any user intending to recover stored water must obtain a recovery permit. The recovery permit holder does not need to be the same as the recharge permit holder, so long as the recoverer has a written agreement with the recharger to recover and use the stored water. Additional permits include those for monitoring wells and injection and recovery wells. Projects that intend to divert water from a stream must obtain a stream alteration permit, and wells that will recharge groundwater must have permits for injections. The injected water must be of equal or better quality than the receiving water.

In addition to the permitting requirements, Utah requires water users to consult with local governments, in part because local laws, such as zoning laws, might affect conjunctive management programmes. In such cases, conjunctive management projects may need special use permits or special construction permits.

2.3. Exempt uses

As described earlier, when an upstream land manager harvests rainwater or alters land use so as to increase evapotranspiration, the activity falls outside government regulations in most jurisdictions. Although the idea that certain uses are exempt from regulation may date back to Roman times it may by time for reconsideration.

Viewed purely in hydrological terms, if the entire system were well managed then any user of water – whether capturing precipitation, withdrawing groundwater or diverting surface water – would need to obtain a permit, just as for any other use. Existing regulations regarding the allocation and prioritization of uses would then determine if the permit should be granted and if so, how pre-existing downstream users would be protected from any potential harm from the additional use.

Although an attractive notion from a hydrological management standpoint, this may not be economically practical. The notion that precipitation and waters flowing across private land and small domestic wells should be considered either the property of the land owner or outside the scope of regulation likely rested on the view that the costs of regulating and managing these resources were high compared to the benefits. As water has become scarce over time, the costs of not regulating such uses may look increasingly high. Similarly, as understanding of hydrology has increased and technologies for remote sensing, hydrological monitoring and modelling have improved, the costs of developing and enforcing regulations on smaller users have fallen.

For these reasons, in certain places and under certain circumstances it is not unusual to see governments either reducing the types and amounts of exempt uses or moving them into a formal permitting system. In the Walla Walla basin of the U.S. State of Washington, for example, exempted uses of groundwater included water for domestic, in-home use and for up to 0.2 hectares of outdoor irrigation. Following rapid growth of residential housing on top of a shallow alluvial aquifer that feeds a downstream fishery listed under the Endangered Species Act, the state enacted regulations in 2007 to limit the exempt uses to in-home use and to require purchase of an offset for any outdoor watering using groundwater.

It is worth noting here that an argument can always be made and will have strong socio-political backing that certain uses should always be exempted, i.e. for drinking water and domestic purposes. However, at least in developed countries, the pressure on water resources from expansion of residential and urban areas can be significant. Most water used in these households is not to meet basic needs and, therefore, may be fair game for new regulations that explicitly recognize, quantify and permit such uses, subject to existing management plans and water availability.

With regard to rainwater, most public policy approaches seem to consider it a "new" source of water. Instead of integrating rainwater harvesting into regulations governing groundwater and surface water, most policy-makers simply pursue economic incentives to promote the technique. Thus, the City of Santa Fe in the U.S. State of New Mexico has set forth three classes of residences and commercial buildings, each requiring a different level of investment in rainwater harvesting. Myriad other tax credit, grants and other market-based instruments are also used to subsidize the instalment of rainwater systems.

Finally, with regard to land management, most regulatory systems do not incorporate downstream considerations, as already noted. The rationale for not including such watershed or hydrological services in a formal regulatory framework is mainly due to the difficulty of evaluating the impacts of land uses and the relative costs. For example, it would be difficult to assess on an annual basis the change in water yield (or baseflow or sediment) associated with a change in land management on a property that included forest, a residence and a number of crop types. It would also be difficult to track any impacts for one property versus all the other properties in the watershed, each with their own location, sub-surface geology, distance to surface waters, etc. The link between cause and effect is not only difficult to predict but also hard to monitor and verify *ex post facto*.

Regulatory efforts have mainly consisted of contractual arrangements for performance, i.e. for the land manager's adoption of a certain set of management practices. Other initiatives focus on positive and negative incentives associated with different land uses. Some other regulatory examples are explored in the next section.

III. CHANGING INCENTIVES THROUGH REGULATION

There are many ways in which regulation can affect the incentives facing land and water users with the goal of managing water in a more integrated fashion. The many tools, instruments and systems can be grouped into four standard categories employed by economists:

- project investments;
- command and control regulation;
- market-based instruments;
- cap and trade systems.

Each of these will now be addressed in turn and illustrated with specific examples.

3.1. Project investments

Project investments refers to the appropriation of government funds to undertake specific on-the-ground projects, e.g. building a dam or re-engineering a stream system. These funds represent direct centralized provision of public goods. This is a well-known and longstanding approach to water resources development, although future project investments may need to shift to ecosystem restoration. As seen below, there will be cases where regulatory tools do not sufficiently balance human and ecosystem uses: they may limit further ecosystem degradation but do not achieve restoration. The government may therefore need to consider using public funds to buy water use and pollution permits back from users in order to achieve ecosystem restoration goals.

3.2. Command and control: establishing limits on use and pollution

Command and control approaches consist of regulations placed on water users (users of water quantity and quality) which either set the level of resource use or pollution or require users to employ a particular technology in connection with their water use. For example, the state may set the level of water pollution that a point source may discharge or may mandate a particular pollution control technology. The command and control approach implicitly recognizes that the use or pollution is a problem, and that regulations are needed and are likely more cost effective than the status quo.

Technology-based standards specify the methods and equipment that must be used to comply with the regulations. Performance-based standards set uniform control targets for all regulated users but, unlike with technology-based standards, the users are given some choice over how the target is actually met. This tends to minimize the costs of compliance.

Overall, the advantage of command and control approaches is that they directly address excessive levels of resource use or pollution. The disadvantage is that they fail to take account of variations in the opportunity costs of resource use and pollution abatement across users. Requiring all users to adopt a specific pollution technology or use only so much water does not necessarily lead to efficient outcomes in terms of resource allocation.

3.2.1. Land use zoning

An example of a command and control tool in land management is zoning, whereby only certain activities are allowed, based on land characteristics, soil suitability or other measures. Zoning in rural areas typically distinguishes between residential zones and zones for different rural production activities such as agriculture, ranching, forestry and wildlife. Generally, zoning has not adequately accounted for the off-site impacts of downstream hydrological services. For example, the value of groundwater recharge areas is typically not taken into account when urban expansion into rural areas is considered. Soil quality is often considered in zoning areas for agriculture, but not the impacts on runoff, recharge and downstream water quality.

Box 9.2 - Environmental Flow Targets in Switzerland

Amongst the purposes of Switzerland's Federal Law on Protection of Water (1991) are to protect water for the "natural functioning of the hydrological cycle" (art. 1(h)). The law also sets out requirements for maintaining a minimum instream flow. It requires permits for any water withdrawals that exceed normal consumption from "permanently flowing watercourses", as well as for groundwater or lake withdrawals if those withdrawals "substantially affect" the flow (art. 29). Permits will be granted if the requirements of the law are met, if the withdrawal does not reduce the rate of flow Q347[3] by more than 20 percent or if the total amount of withdrawal is not more than 1 000 litres per second (art. 30).

The act specifies the minimum residual flow for water bodies, i.e. the "rate of flow of a watercourse which remains after one or several withdrawals of water" (art. 4). These minimum flow requirements may be increased in certain circumstances, such as where water quality cannot be maintained with the water withdrawals and wastewater discharges (art. 31(2)(a)) or where the water depth that fish need for free movement cannot be maintained (art. 31(2)(d)).

When the authorities decide that the minimum residual water flow needs to be increased, they must weigh and balance certain interests in favour of and against demands for water withdrawals. Factors in favour include the public interests that may be served and economic interests of the potential withdrawer. The factors against withdrawal include the significance water has as part of the landscape and "as a biotope for the fauna and flora dependent on it"; the need to maintain the rate of flow for water quality requirements; and the water needs of agricultural irrigation (art. 33). Users wishing to withdraw water must prepare a report that addresses the consequences of the withdrawal, calculates the various flow rates, elaborates the interests the withdrawal will serve and the interests that may be impaired and identifies the measures that could prevent the impairment (art. 33).

[3] Q347 refers to the rate that is reached or exceeded an average of 347 days each year (averaged over ten years) and which damming, withdrawal and water supply do not substantially affect (art. 4).

3.2.2. Environmental flow targets

A command and control approach can also be used for environmental flows, either by specifying the method that must be used to set environmental flow targets or actually prescribing the level of flows that must be achieved. Switzerland's water protection law, for example, requires strict calculations before permitting of new water uses so as to protect minimum streamflows (see Box 9.2). Similarly, the European Water Framework Directive sets "good ecological status" as the performance bar for environmental flows, as already noted. Since many streams and rivers will fail this test, the European Union is using this command and control approach as a tool for restoring environmental flows.

There are a variety of methods available for determining environmental flow requirements in a given system: a recent review found 207 methods across 44 countries (Tharme, 2003). Table 9.1 illustrates the system in South Africa, where existing flow regimes and ecological conditions are classified from natural to poor.

Table 9.1 - Ecological Management Classes in South Africa

Class	Flow Regime	Ecological Condition
A (natural)	Close to natural	Negligible modification of habitat and biota.
B (good)	Largely natural; few modifications	Ecosystem in good state; biota largely intact.
C (fair)	Moderately modified	Loss of sensitive species; some populations in decline; tolerant or opportunistic species may increase.
D (poor)	Largely modified	Habitat diversity and availability in decline; tolerant species present; population dynamics disrupted.

Source: Postel and Richter, 2003.

The decision about the desired flow regime and ecological condition is ultimately a decision for society to make and not just a technical one, as altering water use carries with it a series of social, economic and environmental costs, benefits and risks. Legislation requiring all streams and rivers to attain, for example, Class B (in Table 9.1) may seem the right decision to some but arbitrary to others. It will also result in widely varying costs on the part of those having to meet the required environmental flow regime.

3.2.3. Caps on water use and pollution

An alternative to setting environmental flows is to set limits on water use or pollution. In developed countries, as water resources have become over-allocated, states have often found it useful to "close" basins. By not permitting additional uses of water, the overall resource use is capped. As detailed in Box 9.3, this can be done at a very large scale, such as with the cap on water use set in the Murray-Darling Basin in Australia. Environmental flows were not a factor in setting the cap, whereas in the U.S. State of Oregon instream water rights are included in the calculations of whether a basin should be closed to further appropriation.

Box 9.3 - Murray-Darling Basin Cap in Australia

In June 1993, the Murray-Darling Basin Ministerial Council directed that a study be undertaken on the issue of altered flows and their consequences for the rivers of the Murray-Darling Basin (MDBC, 2003). This led to an audit of water use, which confirmed increasing levels of diversions and associated declines in river health. In response, the Council introduced an interim cap on water diversions in the basin in 1995 and a permanent cap in 1997. In imposing the cap, the Council essentially balanced the social and economic benefits to be derived from development of the basin's water resources and the water needs of the riverine ecosystem.

In 2000, the Council commissioned a comprehensive review of the operation of the cap, which concluded that:

- the cap has supported the Council's aim of achieving the ecological sustainability of the basin's river systems;
- although the cap does not necessarily provide for a sustainable basin ecosystem, it has been an essential first step toward this end;
- without the cap there would have been a significantly increased risk of increased environmental degradation of the river system of the basin.

Caps on pollution discharge are another important tool in regulating environmental quality in waterways. In the United States, the Clean Water Act has been instrumental at limiting pollution and reducing pollution levels. Under the act, waterways must not exceed certain nutrient levels and states must develop plans for remediating waterways back to established levels.

Ideally, such caps would be integrated. For example, closing a basin to surface water withdrawals but continuing to issue groundwater permits makes little sense if groundwater and surface water are hydraulically connected. Equally, since flow in a river is an important factor in nutrient concentrations, there is also a connection to be made between resource and pollution caps. But technical challenges remain. For example, the Government of the United Kingdom has been able to calculate the costs of complying with certain of the nutrient requirements of the European Water Framework Directive but has been unable to understand the flow and quality nexus or to calculate the cost of required flow levels (Acreman and Littlejohn, 2007).

3.3. Market-based instruments

Unlike command and control mechanisms, market-based instruments do not prescribe what water users may or may not do, but rather affect the costs and benefits that users face in the marketplace. In this way market-based instruments can be used to steer private behaviour towards social objectives. The classic example is the polluter pays principle, whereby a tax is placed upon polluters. If the tax is formulated to reflect the marginal external costs of the pollution, then society will in effect internalize these external costs and supply and demand will adjust from market levels to levels that produce an efficient allocation of societal resources. Similarly, if land managers or water users are engaged in practices that have negative outcomes for ecosystems, then government may offer a subsidy or payment to reduce water use or increase water quality.

One advantage of market-based instruments is that they make the opportunity cost of pollution (or water use) clear to the user. In theory, then, the user will work to reduce his or her pollution to the point that the cost of another unit of pollution reduction is equal to the tax on the pollutant. Users will also likely explore all the different means at their disposal to limit their effluent or emission. Another advantage of a tax or payment system is that the tax is set by the central authority and therefore there is no uncertainty (at least within the current tax period) as to the price of pollution.

One problem is that technical information is needed to set the amount of the tax or payment to achieve an efficient level of pollution. There may also be a continuing need to adapt the tax level over time so as to move towards the pollution target. More importantly, there remains no disincentive for those polluters that can afford to pay the tax to continue polluting.

3.3.1. Evapotranspiration taxes and subsidies

South Africa has for sometime been formulating and now experimenting with a tax for any activity deemed a stream flow reduction activity (SFRA). The Water Act of 1998 specifies that afforestation for commercial purposes can be classed as an SFRA and therefore subject to licensing as a water use and to the assessment of charges (Shine *et al.*, 2000).

A tax on evapotranspiration and water use has two impacts. First, it raises the cost to the land manager of engaging in activities that will lower streamflow downstream. All things being equal, this reduces the activity's profitability and may dampen further investment in the activity. Second, the tax provides a source of funds that can be used to offset the impacts of the activity that is affecting streamflow. Unfortunately, independent reports from South Africa indicate that current charges are not yet offsetting water use by plantation forests. Still, the South African legislation provides a useful illustration of how changes in land use that lead to higher evapotranspiration rates can be included in water legislation.

3.3.2. Payments for watershed services

South Africa has a Working for Water Programme which subsidizes efforts to improve land management with a view to improving downstream hydrological services. The main concern is enhancing water supplies, particularly during dry periods. Amongst other activities, local communities (in particular contract labour sourced from previously disadvantaged groups) are paid to remove alien invasive species that have been shown to cause higher water losses. From 1995 to the 2002/2003 budget year, the government spent the equivalent of US$ 300 million and cleared 1.25 million hectares of alien invasive species (Marais *et al.*, 2004).

By comparison, the United States Conservation Reserve Program (CRP) originated largely as a means of tackling non-point source water pollution in agriculture. The CRP is part of the U.S. Farm Bill and provides a range of subsidies to farmers that idle land and undertake conservation measures. CRP represents perhaps the largest national effort to subsidize watershed services. In 2006, the federal government spent US$ 1.9 billion on the programme and from 1986 to 1996 some 14.5 million hectares had been enrolled in the programme with total outlays of US$ 32 billion (FSA, 2007).

Costa Rica and Mexico also have national payment programmes that intend (at least in part) to improve downstream hydrological services. In Costa Rica, the 1996 Forestry Law (No. 7575) recognized the concept of environmental (or ecosystem) services provided by forests, including carbon fixation and sequestration, biodiversity conservation, scenic beauty and watershed protection. The Payment for Environmental Services programme that emerged pays land owners to protect and manage their forests for the provision of these services. The law also makes clear that no forest may be harvested or cleared without the proper government permission.

Mexico's programme, worth US$ 20 million per year, targets the hydrological benefits of maintaining existing high altitude cloud forest areas (Muñoz-Piña *et al.*, 2008). The funds come from the fees paid annually to the National Water Commission by large non-agricultural water users. With payments of around US$ 40/hectare/yr, the programme protects over 300 000 hectares under five-year contractual arrangements.

It is important to note that these payment (or subsidy programmes) are distinct from voluntary contractual arrangements whereby a downstream water user directly pays an upstream land manager to undertake improved practices (or refrain from practices) that will negatively affect downstream services. In such cases the beneficiary pays for the benefit to be received, and except for contract rules, no legislation is required. By contrast, because the national programmes just reviewed are government-run, they require legislation to secure funding and create institutions (Aylward, 2007).

3.3.3. Irrigation water pricing and demand management

Historically, many large irrigation schemes have failed to pay back their construction costs. Even today many such systems do not cover their running costs and are in effect subsidized by public funds. The price for the delivered water is often set according to a fixed allocation and not the amount of water farmers receive. For efficient allocation of water, water should be priced based on the water used, and a progressive tariff should be considered for allocations beyond the base level. An example comes from the North Unit Irrigation District in the U.S. State of Oregon, where farmers pay a fixed price for a base allotment and then pay for additional water on a volumetric basis. Farmers in this district typically turn out half as much water as farmers in other districts in Central Oregon, which instead assess fixed charges based on the land area irrigated.

Where upstream watershed protection is important, additional charges to support beneficial land uses should be considered. For new irrigation schemes full cost pricing should be applied, including any costs to mitigate environmental impacts. The goals of the pricing systems should be made explicit: they may be targeted towards cost recovery, demand management or meeting social or environmental objectives.

3.3.4. Payments for agricultural water conservation

An important source of water is the conservation of existing supplies. There are substantial savings to be gained from improvements in agricultural (as well as municipal and industrial) systems around the world. Direct payments to farmers and irrigation districts undertaking piping, lining and on-farm conservation activities are increasingly proving effective at generating saved water. Irrigated agriculture is estimated to be only about 40 percent efficient on average, with the remaining 60 percent lost through leaky or unlined canals, over-watering of crops and inefficient technology. Because a portion of this lost water typically returns to a waterway or recharges groundwater and is subsequently available for uses downstream, there is the potential for conservation to increase overall productivity of water use (although this will be site-specific).

The United States Department of the Interior operates an annual challenge grant programme – *Water 2025: Preventing Crisis and Conflict in the West* – to provide funds for collaborative conservation. In 2005, the majority of the US$ 10 million went to fund agricultural water conservation projects in the western states. Water from these projects is typically available for other water users in order of priority. However, a number of states provide ecosystem restoration groups with incentives for investment in these projects by allowing the conserved water to be protected for instream purposes. Through its Conserved Water Program, the State of Oregon also allows private investors in a project to capture up to 75 percent of the conserved water and dedicate it to new uses, once 25 percent has been dedicated to instream flows.

3.4. Cap and trade systems

Alongside market instruments like taxes and subsidies are more sophisticated efforts to harness the power of economic incentives. Effective regulation of water use and pollution can be accomplished through the creation of regulated markets for ecosystem services. So-called "cap and trade" systems can be a useful and efficient method for limiting resource extraction or pollution. As described below, such trading systems are developing across the spectrum of water resources management.

A cap and trade system sets an aggregate rather than individual cap on pollution (or resource use). Tradeable allowances take the form of individual quota shares of the aggregate cap. For example, a system of marketable pollution permits requires three steps:

- determining an overall maximum level of pollution (the cap);
- assigning available pollution permits to polluters; and
- allowing polluters to buy and sell pollution permits so long as the total pollution is equal to or less than the cap.

"Mitigation" or "offset" programmes represent a slight expansion of this type of permit system in that they allow third parties to enter the pollution credit market with activities that offset pollution and generate credits. The credits are then sold to polluters. Mitigation programmes require the same three steps, but the emphasis is typically on "no net loss". This means that no overall increase in pollution is allowed: in effect all existing polluters are allocated permits to pollute equal to their current pollution and any new pollution needs to find credits to offset itself, to achieve no net loss.

Cap and trade systems function the same whether pollution or water use is being capped. For water use, of course, it is water rights and not pollution permits that are traded. Although cap and trade systems have as their primary objective holding pollution (or resource use) to a targeted level, once established they may also be used to lower the overall pollutant load or reduce overall resource use. Continuing with the pollution example, if third parties are allowed to purchase permits (or credits), then the price of permits will rise and the supply will be smaller, leading to lower pollution levels. By monetizing pollution, these systems allow for a market to emerge not only in pollution control but also in ecosystem restoration. This is because the existence of a market for permits and offsets makes it more likely that polluters and third-party providers will search for low-cost solutions, which may include restoring degraded ecosystems.

The principal advantages of cap and trade systems are that they allow explicit setting of pollution (and resource use) targets and they reduce the cost of abatement. A related advantage is that they leave price-setting to the market – to buyers and sellers – and not to government officials. The disadvantage is that they leave buyers and sellers with price uncertainty, at least at the initiation of the programme. This can increase political resistance to such schemes by large institutional players and industry. The programmes can also be complex to administer since monitoring, tracking and reporting are required to ensure that the programme meets its targets and that the participants are following the rules. Still, these are largely start-up issues and based on current evidence, a well-designed cap and trade system, at least of pollution management, appears to be cost-effective (Freeman and Kolstad, 2007).

3.4.1. Surface water trading

One problem with a cap and trade system for water rights is that it effectively blocks prospective new water users from acquiring and using water. By contrast, allowing existing water right holders to sell, lease or donate their water rights to others creates a system where low value uses of water can move to higher value uses. If charges are low the water is effectively free and therefore the user is likely to use his or her allocation regardless of its contribution to economic output. Once the system allows the user to trade water rights, he or she can decide whether to use the allocation or trade it. Where the market allows other prospective users to communicate their need and demand for the water, then the user is more likely to choose the use that reflects what society as a whole would choose, i.e. the use with a higher economic value.

The ability to transfer water will lead to more productive use of water in its existing uses as well as provide a source of water to new economically vibrant uses. Such a system also provides a voluntary and financially rewarding way to carry out streamflow restoration where ecosystems are valued by local communities, without taking water from farmers through regulatory or bureaucratic means. As employed for environmental purposes, these approaches are perhaps best developed in Australia and the United States (Garrick *et al.*, 2008).

Perhaps the most ambitious scheme of this type comes from Australia where the federal government has appropriated US$ 10 billion to restore the Murray-Darling Basin. Of this sum, US$ 3 billion has been earmarked for recovering water for environmental flows – through purchase of water rights and through infrastructure improvements that result in water being saved. The money comes with new legislation which will allow the Australian Government to set the sustainable diversion limit for all surface water and groundwater resources of the basin.

In the United States in the State of Idaho, the Bell Rapids Irrigation District sold all of its 10 000 hectares to the state government (for US$ 24 million), which will now lease the water for instream flow to the federal government for salmon and steelhead recovery. Similarly, in the Klamath Basin of California and Oregon, the federal government pays farmers not to pump groundwater so as to provide higher flows for salmon. Elsewhere in the Pacific Northwest, a growing number of NGOs use water leasing and transfers to restore tributary flows for fish, recreation and water quality under the Columbia Basin Water Transactions Program financed by the Bonneville Power Administration.

3.4.2. Groundwater trading

Cap and trade systems for groundwater place a limit on total groundwater withdrawals, distribute groundwater pumping credits and then allow trading of credits between users. In some systems credits are also issued for any additions made to aquifer storage, which provides incentives to invest in aquifer recharge. An active groundwater credit trading system is in place in the Edwards Aquifer in the U.S. State of Texas. Equally, a recharge credit system is being evaluated in Australia with the aim of improving the management of waterlogging and irrigation-induced salinity management in the Coleambally Irrigation Area.

3.4.3. Integrated trading

Another option is a trading system that takes into account both groundwater and surface water, i.e. with an integrated cap. In such a system, the downstream impact of new groundwater withdrawals would be offset by restoring streamflow or recharging aquifers. To ensure that consumptive use is capped, the denomination of the credits traded may need to be in consumptive use units, not units of diverted or withdrawn water. In 2002, the

State of Oregon developed such a cap and trade system for the Deschutes Basin, which has led to the development of markets for both temporary and permanent groundwater mitigation credits. Municipalities, developers and irrigators desiring to develop new groundwater rights must first acquire credits that are created through the retirement of existing surface water rights.

3.4.4. Water quality trading

A final example of changing behaviour through financial incentives is to allow water quality trading. This type of system has emerged in the United States. In 1990, Connecticut, New York, and the United States Environmental Protection Agency agreed on a plan to reduce nitrogen discharges into Long Island Sound by 58.5 percent between 2000 and 2015. Connecticut and New York incorporated the target into a total maximum daily load (TMDL) for nitrogen. To meet its commitment, Connecticut chose to implement a nitrogen credit trading system among point and non-point sources. In its first year of operation, the programme reduced nitrogen discharges by 15 000 pounds, or 50 percent of the target reduction (Aylward *et al.*, 2005).

Trading has also developed for other types of nutrients. For example, in Australia's Murray-Darling Basin, efforts are under way to develop markets for salinity trading. Under the basin's Salinity Debits and Credits Management Framework, states that acquire salinity credits by contributing to salinity-reducing projects may be allowed to increase salinity within agreed limits if they employ salinity debits. In the U.S. State of Oregon, planning is proceeding in the City of Portland to develop a storm water trading system. Developers would have a choice between providing their own on-site mitigation measures, buying credits from third parties or making payments to fund large storm water projects developed by the city.

Whereas water quantity trading between out-of-stream uses has a considerable history and is well developed, efforts to trade water for environmental purposes are still in their early stages and those for water quality are in their infancy. The few examples that exist are in developed countries. It remains to be seen whether there will be additional innovations in other watersheds and in other contexts in the future.

IV. CONCLUSIONS

Water legislation has traditionally been used to establish permit systems for water use and point source pollution and to regulate the development of water infrastructure. Given the poor state of freshwater resources in the world, new approaches are needed. Water legislation should strive to implement integrated water resources management and set the parameters for improved governance across the water cycle. Regulatory frameworks should promote sustainable water use, foster better land management practices and encourage water quality improvements. Institutions and rules should enable water users and land managers to continuously enhance the productivity of water use for human development and ecosystem protection.

Central to this mission will be the need to alter incentives facing water users so that they bear the true cost of their resource use or pollution. At the same time, flexibility is essential to take account of changes in the character and nature of water use, in order to make room for new and higher value uses. A range of regulatory approaches can lead to more flexible, low-cost and adaptive water management. Regulatory frameworks and systems should foster innovation, experimentation and expansion of successful approaches. Examples of improved governance of water resources should be shared widely to help all countries, especially less developed ones, avoid having to relearn the lessons of past failures.

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10

CONCEPTIONS OF WATER [*]

Contents

[*] This chapter was prepared by Jessica Vapnek, Margret Vidar and Victor Mosoti.

This text has reviewed aspects of water management from a variety of perspectives. The overall theme has been one of integration: of legislation and science, of the national and international realms, of quantity and quality, of surface water and groundwater and of human and ecosystem uses. Increases in world population and in global water demand will heighten the need for holistic and integrated solutions to manage water resources sustainably for future generations.

The coming years will see accelerating globalization and an easier exchange of information across national and international boundaries. New scientific and regulatory questions will arise and are sure to attract scholarly interest. The preceding chapters examined a number of innovative approaches to managing water, and introduced several new conceptions of water and water-related services. A key theme of this text has been the importance of ecosystem uses of water, an idea that has been under-valued or absent from many scientific and regulatory approaches to date. This concluding chapter highlights three more conceptions of water and water-related services that may garner increasing attention as the twenty-first century unfolds: water as a commodity, water as a service and water as a human right.

I. WATER AS A COMMODITY

One issue sure to persist on the international agenda is whether water is a tradeable commodity subject to international trade law – essentially, whether water falls within the purview of the General Agreement on Trade and Tariffs (GATT) or other regional trade agreements. The debate will continue in part because the GATT, which regulates trade in goods, does not itself define what a "good" is.

Some commentators who argue that water is a "good" point to the fact that it is not specifically excluded as such from the GATT. Further, they point to its inclusion in tariff heading 22 January 1990 of the Harmonized Commodity Description and Coding System where water is classified as a beverage under the heading "Waters, including natural or artificial mineral and aerated waters ... ice and snow". Other commentators imply that water is covered by the GATT as a "primary product" given that "product" is defined as "any product of farm, forest or fishing or any mineral, in its natural form or which has undergone some processing as is customarily required to prepare it for marketing in substantial volume in international trade" (Annex I; art. XVI).

The notion has been advanced that for water to be considered a tradeable good, it should have been altered somewhat from its natural state by human intervention, for example through some form of production process. Although this argument originates from a plausible premise, it is less clear what would qualify as human intervention and what process would amount to a change of water from its natural state.

A number of GATT provisions are relevant to the debate on water as a tradeable commodity. These include the two key GATT principles dealing with non-discrimination, i.e. most favoured nation and national treatment. The most favoured nation principle requires all members of the World Trade Organization (WTO) to grant each other equal treatment with respect to "like products" originating from or destined to the territories of other WTO members (art. I). The national treatment provision, on the other hand, requires that once "foreign" goods have entered a particular market, they must be treated in the same manner as locally produced or domestic goods (art. III).

In addition to this basic principle of non-discrimination, GATT, Article XI(1), could be relevant to water to the extent that it prohibits the quantitative restriction of imports or exports. Concerns have been raised about whether under Article XI governments would be barred from prohibiting bulk water transfers or would be barred at least from stopping such bulk transfers once they began (Gleick, 2002).

Article XX may also be relevant as it can be invoked to allow a member state to apply an export restriction if it is necessary, amongst other reasons, for the protection of animal and plant life and health or the conservation of "exhaustible natural resources". Whether or not water is an exhaustible natural resource has also been the subject of debate, with some commentators arguing that it is not since it is reproduced through the natural water cycle. However, the WTO Appellate Body has interpreted the term "exhaustible natural resources" in the past to include salmon, clean air and sea turtles and it is therefore probable that water will be considered an exhaustible natural resource.

The Marrakech Agreement which established the WTO is also implicated in the debate. In the preamble to the agreement, countries recognized the importance of an "optimal use of the world's resources in accordance with the objective of sustainable development, seeking both to protect and preserve the environment". One may read into this language the desire to ensure that water resources are managed and consumed in a manner that ensures long-term sustainability even if they are considered a tradeable product under the WTO.

II. WATER AS A SERVICE

The General Agreement on Trade in Services (GATS) covers all service sectors except air transport and those services "supplied in the exercise of government authority" (WTO, 2007). As such, the GATS may affect water management through the water supply, water treatment and sanitation sectors. However, the degree to which the GATS will affect public services (such as health and water services) is a subject of great debate amongst both critics and supporters of the agreement.

Under the GATS, WTO member countries, especially developing countries, are under pressure to liberalize their service sectors and to open up markets to greater competition from private providers including multinational corporations. However, GATS commitments may only be reversed in certain limited circumstances or may require the payment of compensation to other member countries. This could have implications for water management in that a nation wishing to regain control of the provision of water services from a private sector business may find that a costly choice (PSIRU, 2006). In a bid to allay fears that WTO members, especially developing countries, were being compelled to liberalize their water services sector, the WTO Secretariat has stated that under GATS, members are free to pursue different options in this regard, including (i) maintaining a public or private monopoly, (ii) opening the water market to domestic competition, (iii) opening the water market to foreign competition without making a GATS commitment, and (iv) making a GATS commitment to grant foreign companies the right to supply water services in addition to national service suppliers (WTO, 2009).

2.1. Environmental services

The GATS includes 12 categories of services in its list of classifications, which may be changed through agreement or negotiation. Recent attempts to add water under the GATS have sought to include it as an environmental service. For instance, the United States submitted a paper that focused on pollution control and waste management services, and although it did not specifically mention water supply, it did suggest that all environmental sectors should be liberalized, including those sectors that are "related to the core environmental services sectors" (PSIRU, 2006). WTO members have agreed to and have encouraged the liberalization of environmental services, which fall under GATS Classification 6 and include sewerage, refuse disposal, sanitation and "other" (which can include nature and landscape protection and other environmental protection services). The European Community (EC) proposed including water in the environmental services definition, suggesting the addition of "water for human use and waste water management" to the environmental services category (PSIRU, 2006). However, what constitutes an "environmental service" is not yet known: as a case in point, there is debate over whether drinking water provision is an environmental service.

To date, WTO members' support for adding water for human uses to the list of services governed by the GATS has been weak whilst public outcry has been strong. In subsequent requests, the EC left out water for human uses (the collection, purification and distribution of water) but continued to focus on sanitation and sewerage services (Varghese, 2006). This is another example of the uncertainty surrounding the extent of the GATS' reach over water resources management and services, which will depend on future rounds of negotiations. It remains, for some groups, a contentious topic.

2.2. Other water-related services

Although water for human uses has been left out of negotiations and requests in recent years, the GATS does affect other water-related services. In particular, it may limit the actions governments can take to regulate water use, allocate water or establish licensing schemes for water abstraction, service provision or effluent discharge.

Ownership of water resources is a key issue. As noted in earlier chapters, most countries choose to maintain ownership over the resource but allow property rights in the use of the water (usufructuary rights). Some GATS opponents have contended that by agreeing to make liberalization commitments under the GATS, countries' sovereignty will be eroded and their regulatory role circumscribed. Although this argument has also been advanced by WTO members with regard to commitments under other WTO agreements, it has been most pronounced under GATS. As the World Wide Fund for Nature (WWF) and the Centre for International Environmental Law have stated, "[i]f access rights to water are granted in such a way as to embed the right to take for long periods, with compensation payable for any policy changes, the regulatory entities may find themselves constrained, at least financially, in putting in place regulatory changes" (WWF and CIEL, 2003). Put simply, if the government grants water rights to service providers, depending on the circumstances it may need to compensate these providers if it later withdraws or reduces the rights that were granted. Here, the "reversibility" of a GATS commitment is critical. WWF-CIEL concluded that regulators will have to make careful water allocation decisions, as they would likely have difficulties subsequently in altering the legal frameworks.

The issue of a government's freedom to issue licences may raise similar concerns. Licences are a means to grant access to water for uses such as industry, irrigation, livestock watering, water service provision or wastewater discharge. Because licences play an essential role in the management of water resources, limitations set by GATS could potentially affect water conservation efforts. The market access provision specifically prohibits measures that limit the number of service suppliers, the total value of service transactions, the total number of service operations or the quantity of service output, as well as measures that restrict the types of legal entities that may supply a service or that limit the participation of foreign capital (art. XVI(a)-(f)). Hypothetically, if a nation entered into a commitment that involved water abstractions and later established a national policy that contained or resulted in quantitative limitations on the number of licences that could be granted for abstraction, the policy might come into conflict with the GATS rule. On the other hand, it is not yet entirely clear whether and to what extent the market access rules of the GATS would apply; therefore, whether the rules would inhibit the use of licences as a regulatory tool remains an open question.

III. WATER AS A HUMAN RIGHT

Water was once perceived as being abundant and freely available to all, like air. More recently, this perception has ceded to the recognition that access to water is not a given for all people, and challenges such as pollution and climate change are increasing water scarcity. More and more, water is being discussed in human rights terms – as a right in itself and as an issue calling for a human rights-based approach.

3.1. Existence of the right

Water is not explicitly mentioned in the International Bill of Rights,[1] although it is necessary and integral to a number of human rights recognized therein. According to the United Nations Committee on Economic, Social and Cultural Rights (CESCR), the right to water is derived from two articles of the International Covenant on Economic, Social and Cultural Rights (ICESCR), Article 11 (right to an adequate standard of living, including food, clothing and housing) and Article 12 (right to highest attainable standard of health).

The lack of an explicit mention of a right to water has triggered some discussion on whether there is such a right or whether it is more correctly seen as instrumental to other rights. However, access to water is explicitly mentioned in the 1979 Convention on the Elimination of All Forms of Discrimination Against Women (with respect to rural women), the 1989 Convention on the Rights of the Child (regarding clean drinking water for the right to health), the 2006 Convention on the Rights of Persons with Disabilities (regarding clean water services in the context of the right to social protection) and the International Labour Organization Convention No. 161 of 1985 on Occupational Health Services (regarding sanitary installations in the context of a healthy working environment).

A variety of other international and regional treaties, declarations and statements also recognize the human right to water. As early as in 1977, the United Nations Water Conference of Mar del Plata stated that "all peoples, whatever their stage of development and their social and economic conditions, have the right to have access to drinking water in quantities and of a quality equal to their basic needs" (UN, 1977). However, the right to water is not recognized by all such international meetings as a matter of course. For example, at the 5th World Water Forum, the Istanbul Ministerial Statement of 22 March 2009 referred to water and sanitation as a human *need* rather than a human *right* (WWC, 2009a). Civil society organizations attending the forum had sought to change this, since the right to water had been acknowledged in previous drafts, but they were not successful (WWC, 2009b). This points to a lack of universal consensus about whether there is in fact a "right to water". Recent United Nations resolutions also

[1] The Bill of Rights consists of the Universal Declaration of Human Rights (1948) and the two International Covenants, on Economic, Social and Cultural Rights (1966) and on Civil and Political Rights (1966).

refrain from affirming a right to water, whilst confirming that there are “relevant human rights obligations related to equitable access to safe drinking water and sanitation (UN, 2008).

3.2. Content of the right

The right to water is defined by the CESCR in its General Comment 15, which states that the “human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses” (UN, 2002). Discussions about the content of the right to water focus primarily on drinking water and other domestic uses, such as washing, cleaning and cooking. This aspect is fairly easy to define and enjoys increased recognition as a human right. Other uses are also relevant to human rights, in particular water for food production (linked to the right to food) and for environmental services (linked to the right to health).

Although water uses for subsistence food production and watering of household animals may to some extent be considered to fall within the right to water and the right to food, it should be borne in mind that the right to food does not convey a universal right to produce food, but rather that people should be able either to produce it or buy it (UN, 1999). It should also be noted that CESCR has stressed adequate access to water for subsistence farming and livelihoods of indigenous peoples, according to the prohibition in the two International Covenants (see footnote 1) against depriving a people of its means of subsistence (UN, 2002). It may also be argued that there is a right to water for food production to the extent that it is necessary to satisfy minimum essential levels of realization of the right to food, for those who depend on subsistence agriculture (UN, 1999).

There are three main aspects of the content of the right to water in the narrower sense: quantity, quality and accessibility (UN, 2002). For quantity, adequate household needs for ensuring that all health concerns are met have been defined by the World Health Organization as 50–100 litres per day, depending on the circumstances (Howard and Bartram, 2003). An absolute minimum to maintain life is considered 25 litres per day, but this is not sufficient to maintain hygiene, for instance (Hutton and Haller, 2004). Needless to say, the quantities needed for food production and environmental services are much higher. Therefore, beyond household needs (which should enjoy priority (UN, 2002)), human rights provide only limited guidance on how to prioritize the different needs. As regards quality, CESCR's General Comment 15 states that water for personal and domestic uses must be safe and free from substances constituting a threat to a person's health (UN, 2002).

Discussions about accessibility of water distinguish between physical and economic accessibility, and also include the question of equitable access and non-discrimination. Physical accessibility refers to the distance from home, school or workplace a person has to cover to collect water or to use water services. Economic accessibility refers primarily to affordability, in particular for the poor. As noted in earlier chapters, the poor in urban areas often have to pay more than the middle classes for their water (UN, 2007). Closely linked to this issue is the question of disconnecting households from water supplies for non-payment of water charges, also discussed earlier. Within the context of the right to water, it may not be considered lawful to deprive persons of their basic water needs of around 50 litres per day if they are unable, for reasons beyond their control, to pay the charges.

3.3. Realization of the right

The recognition of water as a human right triggers corresponding state obligations. Experts on socio-economic rights have developed an analytical framework which explains that rights such as the right to water carry both negative and positive obligations (Eide, 1989). The right to water thus carries obligations by the state to respect, protect and fulfil the right. The obligation to *respect* means that the state must refrain from interfering with existing access to safe drinking water in terms of availability and quality. The obligation to *protect* obliges the state to enact adequate legislation to ensure that non-state actors do not interfere with access to water, for example by depleting groundwater or polluting water resources. When water services are operated by the private sector, the obligation to protect means that the state must enact an adequate regulatory framework and controls to ensure equitable and affordable access to water. The obligation to *fulfil* can be disaggregated into the obligation to facilitate, promote and provide access to water.

In practical terms, a country that wishes to ensure that it complies with its obligations with respect to the right to water must first assess who does not have access to affordable and safe water and whether the current policies and programmes are sufficient to ensure that this will be redressed. Drinking water policy must be deliberate about ensuring affordable access to the poor without discrimination. There is a need for constant monitoring of progress towards better access, both from a technical and from a human rights point of view. Civil society can play a major role in empowering rights-holders to know and claim their rights with regard to water and in demanding better policies through advocacy and lobbying. Civil society can also usefully monitor state efforts to realize human rights, either independently or in cooperation with national human rights institutions.

A number of countries recognize the right to water as an enforceable human right in their constitutions (e.g. Bolivia, Ecuador, South Africa, Uruguay). Many other countries recognize the right to water not as an individual right, but as a directive principle of the state, which may not be directly enforceable by courts (e.g. Cambodia, Colombia, Eritrea, Ethiopia, Gambia, Guyana, Iran, Laos, Mexico, Nigeria, Panama, Portugal, Uganda, Venezuela). Access to water or its protection is often linked to other human rights, such as the right to environment (as in Cambodia, Laos and Panama), the right to natural resources (as in Eritrea and Uganda) or the right to property (as in Mexico).

A number of countries have recognized the right to water in their national legislation (e.g. Algeria, Belgium, Burkina Faso, Ukraine). Disconnection from domestic water supply for non-payment has been forbidden by law or case law in many countries (e.g. Argentina, Australia, Austria, Belgium, Brazil, Ireland, Luxembourg, Mexico, New Zealand, Norway, Spain, Sweden, Switzerland, Ukraine, United Kingdom) (Smets, 2006).

3.4. Process of achieving the right

A human rights-based approach to water management combines a focus on the outcome (that everyone, in particular the most vulnerable, has access to safe, sufficient and affordable water) with concerns about the process employed to achieve that outcome. The key rights involved are the right to information, the right to participation and the right to a remedy.

Information
Implementing the right to information means ensuring that users of water are informed about the water distribution process. For example, water users should be informed of water quality, prices and any major decisions that water managers might make (Smets, 2006). This type of transparency allows

users to hold government authorities or water distributors accountable for any failures to comply with the law.

Many countries already require that information on drinking water be distributed to the public. This information can include data on the quality of drinking water and annual reports that are published by water service managers (Smets, 2006). It should also include information on government activities, for example, if the government is considering amending its laws or policies or authorizing activities that may have a harmful effect on water resources.

Participation

The right to participate implies the right of users and those otherwise affected to actively participate in water development and management (Filmer-Wilson, 2005). Participation, to be effective, requires access to education and information, a role in decision-making and monitoring processes and mechanisms for redress (Scanlon *et al.*, 2004). A knowledgeable public is better able to react and make its voices heard (Scanlon *et al.*, 2004).

Public participation may include the formation of committees that have certain rights or duties with respect to water management organizations or companies. The public may also participate through representative bodies with which the government must consult before making decisions. Some countries (e.g. Honduras) are obligated to carry out public surveys or referenda before making any major decisions such as privatization of the water supply. Other countries (e.g. United States of America) hold hearings before making decisions, to answer any questions or respond to any comments or concerns the public might have (Smets, 2006).

Remedies

The right to a prompt and effective remedy is essential for government accountability. This means that administrative recourse should be easily accessible at all levels, for example to enable the public to challenge unfavourable decisions regarding water allocation or management. In addition, national human rights institutions in many countries can receive complaints about violations of the right to water and recommend suitable remedies. Unless access to courts is secured as a final recourse, however, these other remedies may be ineffective.

The right to an effective remedy goes beyond access to administrative or judicial processes. Where mechanisms to enforce rights are inadequate or ineffective, governments may need to provide new and more effective ones (Scanlon *et al.*, 2004). States also have a responsibility to ensure that individual rights are not infringed by government or private actors.

IV. CONCLUSION

Many writers have labelled the twentieth century as the century of water resources development and over-exploitation. The hope is that the 21^{st} century will see comprehensive approaches to water resources management which will more effectively allocate water and maximize efficiency of water use. As seen throughout this book, there are scientific and regulatory barriers to achieving this goal, and all must be addressed together.

The scientific component requires continuing work toward a detailed understanding of the water cycle and the variety of ecosystem and human needs within a watershed. To be most effective, water legislation must reflect the latest scientific understanding, whilst taking into account socio-economic and equity concerns.

Given the wide variety of available water resources and existing legislative frameworks, each country will face unique challenges in transforming its water resource management system. For example, many countries are subject to binding international agreements or make use of shared water bodies that are managed by transnational entities, which may constrain their ability to access the water or control its quality. Countries may also have to harmonize domestic legislation where different laws assign responsibilities for water to a variety of agencies or ministries. Governments must devise cross-sectoral strategies and solutions to implement integrated management.

It is hoped that this book will help lead to a better understanding of the steps necessary to design and implement effective water resources management systems underpinned by strong regulatory frameworks. Water plays a pivotal role in every aspect of human life, from economic growth and social development to health. Continuing efforts are needed to improve national and international responses to growing water scarcity. Well-designed management and regulatory systems will make it possible to provide water where and when it is needed for the full range of human and ecosystem uses.

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