IDEAS FOR GROUNDWATER MANAGEMENT

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IDEAS FOR GROUNDWATER MANAGEMENT

Irrigating from the shallow aquifer in Mazandran, Iran – reducing high water tables

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1| INTRODUCTION

Entrance to stepwell, Guadalquivir plain, Spain

Groundwater is best described as the world's real hidden treasure. Almost everywhere it has made a difference in providing safe drinking water and livelihood security in times of drought.

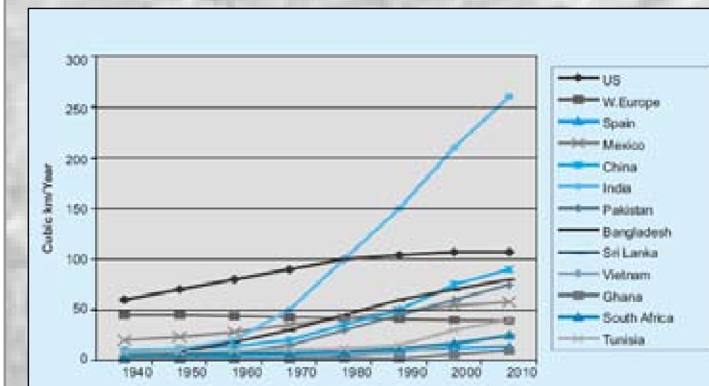
Groundwater is the earth's largest accessible store of fresh water (excluding ice sheets and glaciers) and constitutes about 94% of all fresh water. The volume of groundwater is almost 100 times that of surface water – about 10,530,000 km^3. Groundwater is the most reliable source of supply for potable water and supports a wide array of economic and environmental services. Despite the long history of groundwater extraction throughout civilization, it has only been during recent decades that the use of groundwater has grown exponentially. Estimates of global groundwater abstraction between 1950 and 2000 increased to 1000 km^3 of water in 2000 with more than 2 billion people depending on groundwater for their daily supply. Not only have population increases and economic growth laid claim to an ever larger share of groundwater, but the quality of the resource is also increasingly under strain. As use of the resource has increased, so has its value and vulnerability, forcing 'the hidden treasure' into the spotlight.

Major agricultural economies in arid and semi-arid regions are sustained by groundwater use. The development of pumps and drilling technologies along with government subsidies have allowed groundwater to become a new frontier in resource exploration. Compared to surface water, the development of groundwater has brought many advantages. Groundwater for example, is less vulnerable to sudden changes in availability, offering a better insurance against climate variations. Furthermore, irrigation with groundwater needs little transport from source to plot and offers individual farmers water on demand. In India, the use of water from substantial and easily-accessible aquifers has allowed people to circumvent the inconvenience of poorly

Global groundwater assessment – some numbers

Groundwater use in agriculture has increased exponentially, being the single most important factor that changed the lives of millions of farmers. Even then, the world is still using only a fraction of earth's known groundwater reserves. At less than 1000 km^3/year global groundwater use is a quarter of total global water withdrawals but just 1.5% of the world's annually renewable freshwater supplies, 8.2% of annually renewable groundwater, and 0.0001% of global groundwater reserves (estimated to be 7-23 million km^3)(Howard 2004). Even so in countries like Yemen, India and China farm rural economies are under threat because of very intensive use of groundwater, whereas in urban areas in Mexico and Japan land subsidence plays havoc with vital infrastructure.

Below is an estimation on the development of groundwater withdrawal. The countries shown are those with the highest abstraction rates (Shah, 2005).



functioning public systems or polluted surface waters on a large scale.
In Libya the populated agricultural strip in the north receives a daily supply of water from a man-made river which transports 6.5 million m^3 of high quality groundwater from the Nubian aquifer in the south.

Resource abstraction and pollution come at a price. Many examples, brought forward in this ideas book, show that groundwater is being depleted, and as natural or anthropogenic sources emit hazardous materials, aquifers become prone to salinisation and compaction.

The sustainable management of groundwater resources requires good planning and concerted efforts. In addition to responding to acute resource degradation, planning for groundwater protection needs the attention of all users.

Groundwater irrigation in the bas-fonds, Senegal

Ministerial conference, Kyoto 2003

"Whilst groundwater storage is vast (over 99% of fresh water reserves), its rate of replenishment is finite and mainly limited to the shallower aquifers, whose quality can also be seriously (and even irreversibly) degraded. Excessive resource development, uncontrolled urban and industrial discharges, and agricultural intensification are causing increasingly widespread degradation of aquifers"

AIM OF THE IDEAS BOOK

The aim of this book is to provide ideas on different aspects of groundwater management. This ranges from areas where there is an abundance of subsurface water to areas where the resource is scarce. It is our conviction that in both circumstances groundwater needs to be managed. The book is aimed at the various players faced with challenges in groundwater management, practitioners from local and central governments, non-governmental organizations, groundwater management projects and the users themselves. The book communicates practical ideas – on 'what can be done', gathered from a variety of sources. For those interested in more detail and support, a list of organizations and initiatives involved in specific areas of groundwater are found in annex 2 and 3 respectively.

The book is set up in such a way that it can be browsed through. It is not necessary to read it from start to finish.
Understanding groundwater, regulating groundwater, promoting recharge and managing groundwater quality are presented in Chapters 2 to 5. Chapter 6 gives ideas on groundwater management organizations. Building awareness is presented in

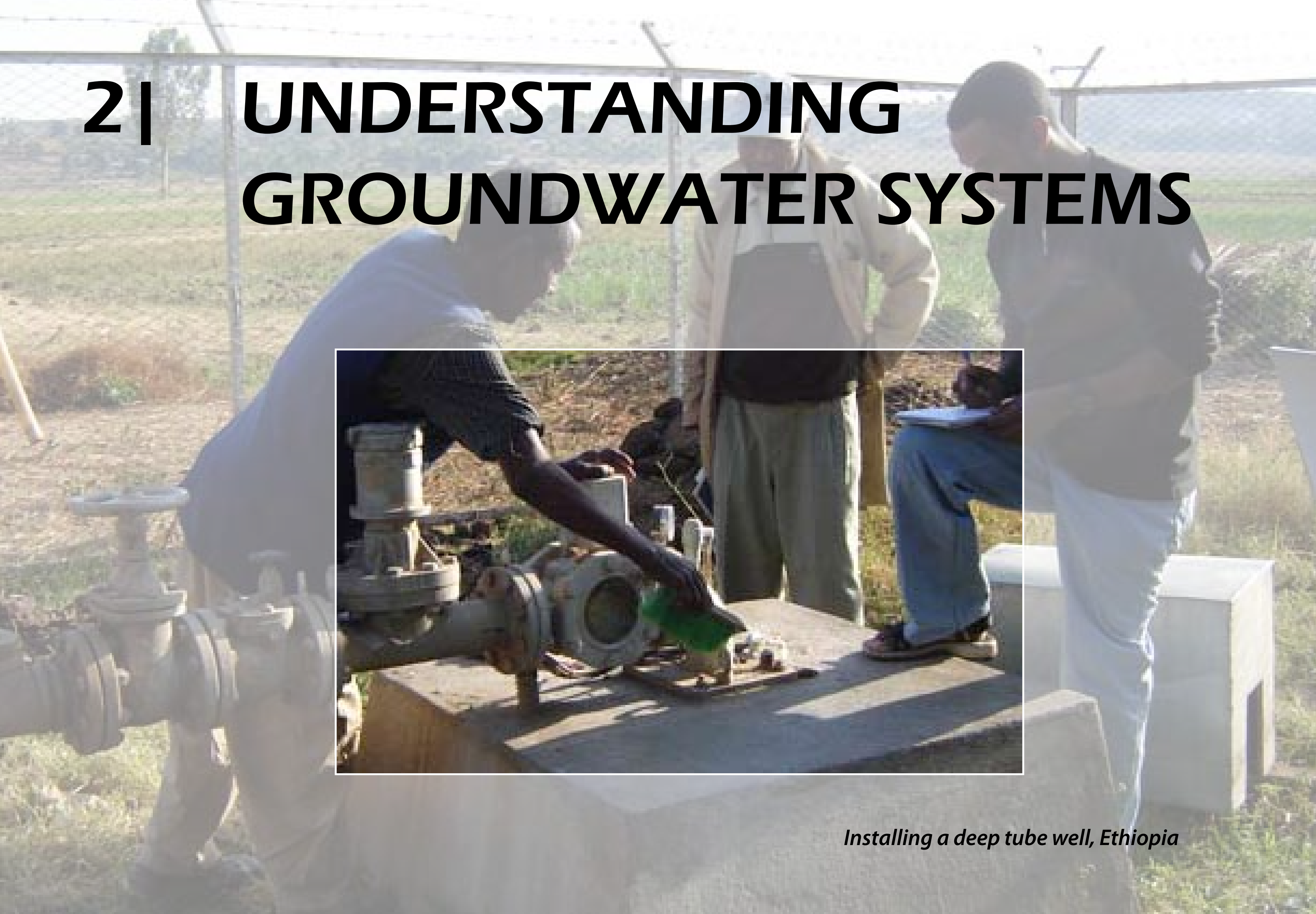
chapter 7 and in chapter 8 some special cases of groundwater management – conjunctive management of groundwater and surface water, groundwater in small islands and transboundary groundwater management – are discussed.

This Ideas book is part of the "Ideas for..."series. Already published are:

- Ideas for Water Awareness Campaigns
- Ideas for Local Action In Water Management
- Ideas for Flood Management
- Ideas and Experiences in Mainstreaming Environment and Water

The ideas come from peer-reviewed articles, books, project documentation, information from the internet, brochures and personal communications. All attempts have been made to stay as close to the original documented initiatives as possible. This book does not pretend to be complete or exhaustive; it merely aims to present a range of options and activities, based on experiences in different parts of the world. Due to the variation in local circumstances (climate, concentration of contamination, geographical place, culture, economy etc.), approaches suitable for one location obviously are not automatically transferable elsewhere.

2| UNDERSTANDING GROUNDWATER SYSTEMS



Installing a deep tube well, Ethiopia

Being invisible, it is hugely important to understand aquifer systems: the basic hydrogeology, the groundwater flows, the depth of groundwater and the sustainable aquifer yields. It is not only important to investigate groundwater systems, but also to share the knowledge in a way that it is widely understood. Without such shared understanding, it will be difficult even impossible to discuss joint management.

2.1 MONITORING GROUNDWATER RESOURCES

2.1.1 MONITORING GROUNDWATER QUANTITY AND USE

Water-level measuring devices

There are numerous types of equipment that are available for measuring depths of groundwater tables. Sophisticated water-level loggers or divers are able to measure automatically the groundwater level and the groundwater temperature, and in combination with data loggers the measuring equipment encapsulates a powerful monitoring tool. In day-to-day use, well dippers and sounding devices with acoustic and light signals are also practical and widely used to check groundwater levels.

Installing tube well flow-meters
Yemen

The government of Yemen has made the installation of meters on wells compulsory. This comes with the new water legislation. The idea is that the information from the meters will inform the analysis of water balance scenarios, which will ultimately be used in decisions on water allocations from surface and ground sources.

Low-cost groundwater level measuring

With very simple and cheap tools, it is possible to make a groundwater level measuring device:
Attach a hook to a 15 cm long, 2.5 cm diameter galvanized pipe. Attach to this hook a rope with a knot at every meter. At the bottom of the pipe insert a rubber cork.
Another option is to use the cover of a film roll and apply a tape measure against it with iron wire. The open side of the film roll cover should face downwards.

When the tools are lowered into the PVC pipe or well, a "plop" sound is heard. At that moment the groundwater levels can be read from the tape measure or rope.
When a tape measure is fully covered with chalk and lowered into the PVC pipe or well, the chalk will be washed away where it has had contact with water.

GPS applications for monitoring

Since the Selective Availability of remotely sensed geographic coordinates was released by the US government in May 2000, GPS Tracking Systems have been used for a wide range of activities for example in worldwide navigation, map making, land surveying, commerce, and scientific uses.
In their effort to counter illegal drilling, the government of Yemen intends to install GPS-tracking devices on the drilling rigs. Alongside stronger partnerships with local authorities, and a violation telephone line, the GPS fleet tracking system hopes to record all activities in Yemen to counter the illegal drilling of new wells.
Precision agriculture in the United States is a technology that is receiving attention from industry, researchers and farmers. Precision agriculture is applying the right amount of inputs at the right time at the right place. Combining the GPS and GIS applications, maps of the actual applied fertilizer, pesticides and water will be generated and reflect the management practices.
GPS and related applications prove to be a helpful tool in conserving water and limiting water degradation.

Groundwater modelling

Groundwater flow models are used to calculate the rate and direction of movement of groundwater through aquifers and confining units in the subsurface. These calculations are referred to as simulations. The simulation of groundwater flow requires a thorough understanding of the hydrogeological characteristics of a site. There are numerous models to simulate groundwater flow from analytical models which offer an exact solution of a specific, greatly simplified, groundwater flow to numerical models that are capable of solving more complex equations that generally describe multi-dimensional groundwater flow and solute transport. Both Modflow and Microfem are examples of numerical models which are widely used and can be downloaded from the internet for free. The outputs from the model simulations are the hydraulic heads and groundwater flow rates which are in equilibrium with the hydrogeological conditions defined for the modelled area.

Isotopic tracing of recharge zones

Uttaranchal Rudraprayang district, the Himalayas, India

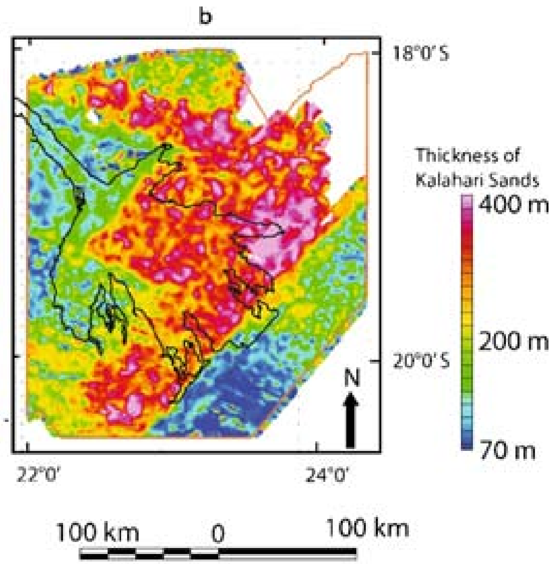
The isotope method is used to track the direction of groundwater flows. The isotope technique has been used to revive 16 drying springs in the Kameda, Gagotu and Nagrasu valleys in the Himalayas. Previous haphazard construction of rainwater harvesting structures had yielded an inadequate supply of water. However, through collaborating with a local NGO and supported by scientists from the atomic research centre, oxygen and hydrogen isotopes can be tracked down from the local springs to their origin and their natural recharge zones. Recharge trenches, check dams, bunds and percolation ponds were built to collect, store and recharge rainwater in the identified zones. Commercial trees like the mulberry and *Grewia optiva* were planted in the vicinity to increase soil stability and percolation.

Remotely sensing aquifer thickness

Okavango delta, Botswana

The applicability and value of remote sensing and GIS applications in land mapping, soil and water conservation etc. has increased enormously in the last three decades. In Botswana high-resolution magnetic surveys were conducted covering the whole country with the primary aim of exploring subsurface formations, bearing diamonds and other minerals. The aeromagnetic data mostly records the magnetic effects of rocks and dikes immediately underlying the non-magnetic sedimentary cover, including the Kalahari sands aquifer and Okavango delta. The depth of this aquifer to the top of the underlying magnetic rock could be estimated at any location and is presented in the figure underneath. The depths of the sedimentary aquifer measured from drill holes and those determined through remote sensing correlated well. The maps can be further used for estimates of aquifer recharge and aquifer volume, providing valuable information for the management of wetland systems, such as the Okavango delta.

Thickness of aquifers estimated through magnetic surveys, Botswana



Subsurface reconnaissance and groundwater survey methods

In order to have an understanding of the groundwater resources, a hydrogeological investigation should include a complete characterization of the following:

- Subsurface extent and thickness of aquifers and confining units (hydrogeologic framework)
- Hydrologic boundaries (also referred to as boundary conditions), which control the rate and direction of movement of groundwater
- Hydraulic properties of the aquifers and confining units
- A description of the horizontal and vertical distribution of hydraulic head throughout the modelled area for both beginning (initial conditions), equilibrium (steady-state conditions) and transitional conditions when hydraulic head may vary with time (transient conditions), and
- Distribution and magnitude of groundwater recharge, pumping or injection of groundwater, leakage to or from surface-water bodies, etc. (sources or sinks, also referred to as stresses). These stresses may be constant (unvarying with time) or may change with time (transient).

Some of the methods for surveying substrata and groundwater are: geotechnical drilling, monitoring wells, interpretation of topographical maps, satellite imagery, recharge estimation using a surface electrical resistivity method or (natural) tracers to monitor (e.g. isotopes), and multilevel sampler wells.

Remote sensing to monitor groundwater use

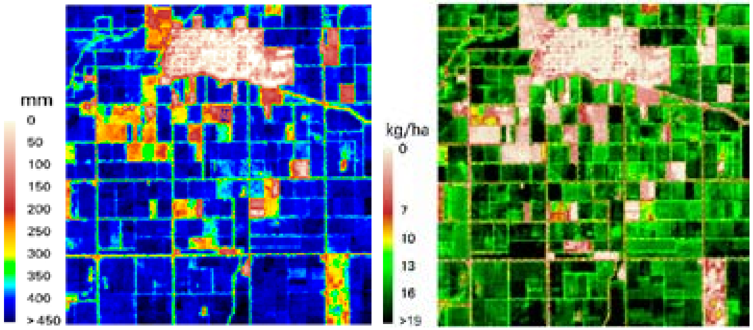
With the use of remote sensing data and technologies it is possible to determine how much water is being used by the agricultural sector. With satellite images evapotranspiration can be calculated for a whole year for each individual plot (pixels of 30mX30m), as shown in the figure below. This makes use of an algorithm called the Surface Energy Balance Method (SEBAL). SEBAL is an image-processing model comprised of 25 computational

Dowsing for groundwater

The technique of dowsing for water has for millennia facilitated finding hidden underground water resources. Cave paintings dated from 9000 years ago in the Atlas Mountains of North Africa and in Peru depict men holding forked dowsing sticks, Confucius (2500 BC) mentions dowsing in his writings, and the Egyptians show evidence of this practice in their stone drawings and carvings. During the Reign of Queen Elizabeth I (1558–1603), English landowners brought dowsers from Saxon Germany to locate the rich tin fields of Cornwall, which are still producing tin today.
Dowsers use a variety of tools such as scissors, coconut shells, Spanish needles, pliers and welding rods. Dowsing techniques differ; the most common is a forked stick. The dowser holds the stick in front of him, which will point downwards when it is held above a groundwater body. There are numerous situations recorded where dowsing techniques have been useful. For example, the six communities on the Verde Islands have limited water storage capacity, poor permeability, lack of extended aquifers and salt intrusion. However one community did not face water shortage problems possibly because their wells had been sited by a local dowser.

Although there is much scepticism surrounding dowsing, it is a global practice and dowsers are considered as local groundwater experts. In Qila Saifullah, Balochistan, Pakistan, dowsing experts are hired for at least 500 US$ to find groundwater. As dowsers are important local groundwater experts, they should be actively involved in creating broad awareness on groundwater and possible overuses.

Dowsing for groundwater in Ethiopia and Pakistan steps that calculates actual evapotranspiration and potential evapotranspiration. This tool can be used for monitoring groundwater use levels and making hydrological balances.



Detailed actual evapotranspiration and biomass production in the north of Mexico

Public access to groundwater data
Punjab, Pakistan

In compliance with the Chief Minister's vision for transparent and equitable distribution of irrigation supply, a special Programme Monitoring and Implementation Unit (PMIU) was created in Punjab, Pakistan. The unit is designed to disseminate information such as; state water allocation, canal supplies and distribution, and checking of gauges and discharges. The groundwater levels, quality and temporal changes are digitized and made available for reference. Farmers in the seven groundwater units in Punjab State have access to information on the quality and quantity of groundwater for irrigation and are advised on the judicious use of the resource.

2.1.2 MONITORING GROUNDWATER QUALITY

Water sampling and field analysis sets

To get a first global impression of the quality of (ground) water, sampling and field analysis sets can be used. The tests help establish the presence of any parameter and the extent to which it is present in a particular waterbody. The initial analyses of the quality of water typically includes measurement of the pH and Electrical Conductivity (EC). This can be carried out using individual instruments for each parameter or multimeters, which measure multiple parameters. The pH of soil and groundwater are important criteria in agriculture to decide on the variety of crops to grow, the amount of fertilizer to apply, or the environmental measures to be taken. The EC is an indication of the amount of salt dissolved in water. There are a variety of water quality test kits which allow field analysis of collected water samples, specifically for sulphate, pH 0-14, nitrate, ammonium, fluoride and arsenic. Test kits that are for educational purposes can include safe and non-toxic test strips to assess the amount of free chlorine, total chlorine, copper, hardness (refers to the mineral content of the water), iron, nitrate, nitrite and pH. UNICEF has developed a very simple kit using the H_2S Strip test to test for bacterial contamination. For purging and sampling the monitoring wells a variety of pumps is available including: submersible pumps, peristaltic pumps, and foot or hand-operated valve pumps.

Passive Diffuse Sampling
Missouri , USA

In Missouri, a method for measuring groundwater quality (Passive Diffuse Sampling) has been widely used. A plastic bag is filled with distilled water and suspended in a monitoring well. Groundwater, including certain contaminants, diffuses into the bag. Two weeks later the distilled water contains the same amount of contaminants as the surrounding water. The plastic bag can be removed and a sample can be taken. In addition to reducing sampling costs, this method also saves water as it is not necessary to purge the well prior to collecting samples.

Avoiding fluoride in drinking water
Andhra Pradesh, India

In South India, increased exploitation of groundwater for irrigation leads to high levels of fluoride in drinking water, as groundwater is pumped from deeper layers that contain higher levels of fluoride. In the village of Battuvani Palli, the NGO Acción Fraterna and the local community joined together to develop solutions. Many villagers were suffering health problems due to concentrations of fluoride close to 3.5 mg per l, i.e. 2-3 times higher than the acceptable level. Using portable fluoride kits to test their groundwater provided the villagers with a better understanding of the source of the health problems. Having assessed the various wells in the village, an irrigation well with safe fluoride levels was identified to be the best source for drinking water. Battuvani Palli was lucky as there was at least a safe well. This is not always the case.

Rapid water testing kits for coliforms and E.coli

B2P is a company in New Zealand which delivers rapid water testing kits for fresh water as well as saline water. The water is tested for coliforms and E.coli (bacteria naturally occurring in intestines, but which can cause diseases when they occur in the wrong places in the body). The B2P testing kits are easy to use. Samples can be tested at home, non-technical people can use them and the results are available in 2-15 hours. The testing kit is colour sensitive, thus depending on the final colour of the sample one can determine whether or not the water is contaminated.

B2P water testing kit. (blue: no coliforms in sample, pink: presence of coliforms, white: presence of E.coli)

2.2 INFORMATION SHARING

With new communicational methods information on groundwater is becoming more accessible to a larger audience. Internet-based systems are expanding as well as informative signs along roads. Chapter 7 includes information-sharing methods as well.

Using hydrogeological maps

The first sources of information on existing groundwater resources are often from hydrogeological maps. The maps provide a starting point for an understanding of the role groundwater plays in the environment. Hydrogeological maps focus on aquifers and aquitards, describing the location of different formations, which convey groundwater or are impermeable. Hydrogeological maps containing extremely useful information, but are generally very difficult to read. Field research in Ethiopia showed that their readability greatly improved when basic topographical details, such as roads and towns, were projected onto the maps.

Pollution locator and Hotline

USA

The scorecard website (www.scorecard.org) contains a tool called "pollution locater" which can be used to find out information on various kinds of pollution such as animal waste and smog, but also on groundwater pollution in the USA. The pollution locater indicates a polluted area and provides information on who is responsible for the pollution by presenting a list of companies and their contribution of toxic chemicals to the water. It is possible to search by state or by zip code. In addition, in Santa Clara County

Classification component

Aquifer Class: the combination of the three development and three vulnerability subclasses results in nine aquifer classes (see below).
The development class is determined by assessing demand versus the aquifer's yield or productivity. The vulnerability class is based on type of aquifer materials, thickness and extent of geological materials overlying the aquifer.
For example, a class IA aquifer would be heavily developed with a high vulnerability to contamination, while a IIIC would be lightly developed with low vulnerability.

Development Sub-class

I	II	III
Heavy (demand is high relative to productivity)	Moderate (demand is moderate relative to productivity)	Light (demand is low relative to productivity)

Vulnerability Sub-class

A	B	C
High (highly vulnerable to contamination from surface sources)	Moderate (moderately vulnerable to contamination from surface sources)	Low (not very vulnerable to contamination from surface sources)

Aquifer Class

	I	II	III
A	**IA**-heavily developed, high vulnerability aquifer	**IIA**-moderately developed, high vulnerability aquifer	**IIIA**-lightly developed, high vulnerability aquifer
B	**IB**-heavily developed, moderate vulnerability aquifer	**IIB**-moderately developed, moderate vulnerability aquifer	**IIIB**-lightly developed, moderate vulnerability aquifer
C	**IC**-heavily developed, low vulnerability aquifer	**IIC**-moderately developed, low vulnerability aquifer	**IIIC**-lightly developed, low vulnerability aquifer

California, residents of the Llagas Groundwater Basin area can call the groundwater protection hotline to receive information on the local nitrate testing programme.

Aquifer classification system
British Columbia, Canada

To support groundwater management in British Columbia an aquifer classification system has been developed. The aquifers in the system are classified according to their vulnerability to contamination. The aquifers are also ranked related to water use. The system is applied to areas in the Fraser River Basin where a total of 153 aquifers have been identified. From the system, it is possible to conclude that from the total amount of aquifers, 132 are used for drinking water, 9 are highly vulnerable to contamination and in 13 aquifers health risks are present. In the box on classiciation component, the classification system is outlined.

Groundwater flow systems classification
Australia

In Australia salt occurs naturally in landscapes. Over thousands of years significant amounts of salts have accumulated in sub-soils. Salts that were once found deep below the surface are now being mobilized due to rising groundwater tables. To understand the salinization processes it is important to understand groundwater processes. Therefore, the Groundwater Flow Systems (GFS) classification has been developed which can eventually be used for salinity management. The GFS framework aims at classifying (sub) catchments through assessing their ability to significantly impact the salinity problem, prioritizing areas, targeting management and 'implementing' salinity management plans.

Groundwater 'beliefs' and misconceptions

A common 'belief' is that groundwater is from an underground river or lake that has no limits. However, most subsurface water flows through fractures in the bedrock, through millimetre-sized openings between geological layers, and between soil particles.
Another belief is that surface water is far more plentiful than groundwater in the world. This is true but only if we include the water in our world's oceans (which represents 97% of Earth's water). Another 2% is stored as frozen water. Of the remaining 1% of water, about 4% is in rivers, lakes and wetlands, a small amount is in the atmosphere, and groundwater accounts for the remaining 96%. However, much of the world's groundwater is not easily accessible for human use.

Often people think that groundwater and surface water are separate. However, groundwater, surface water, and atmospheric water are intimately related through the earth's water recycling machine, known as the hydrological cycle. Water passes repeatedly through all three parts of the cycle.

Sometimes people think that all groundwater is suitable for drinking. Although flow through the ground does have a purifying effect on water by filtering sediment, bacteria and certain chemicals, the purification effect is limited. Large concentrations of chemicals may be impossible to remove completely, and certain chemicals may not be removed by the ground at all. Some groundwater is naturally unsuitable for drinking because of the minerals it has dissolved from the rock through which it flows.

3| REGULATING GROUNDWATER USE

Failed regulation: farmers irrigating grape orchards by tanker, Yemen

There is significant concern that groundwater levels are declining due to intense aquifer use. In many parts of the world these concerns are justified and the future looks uncertain especially where farm economies and domestic water supply systems are strongly dependent on groundwater.

However, in other areas, fluctuation in the water table is an annual or multi-annual phenomenon, with water levels rising at the start of the rainy season or after a series of wet years. In other areas a decline in shallow groundwater actually saves water as less water evaporates from shallow depths – or in technical terms the 'non beneficial evaporation' is reduced. In other areas, groundwater depletion prior to the rainy season helps to create a larger buffer to store excess water and reduces the risk of floods.

This chapter examines areas where the decline of groundwater is a serious threat to livelihoods and local economies. There are several examples where a crisis was responded to by introducing groundwater regulation, i.e., rules that restrict pumping or well development (3.1); and economic incentives (3.3). In addition there are a range of measures that can reduce consumption (3.2). Often all these measures go hand-in-hand.

3.1 RESTRICTIONS ON GROUNDWATER USE AND WELL DEVELOPMENT

In a limited number of places effective local restrictions on groundwater use are in place. The effectiveness of such restrictions is often linked to their simplicity and visibility. Rules that are easy to monitor are often the easiest to implement. Examples are: minimum distance rules, zoning, bans on certain crops or bans on certain types of wells.

Banning high water consumption crops
Saudi Arabia

Banning the cultivation of crops, such as bananas or rice, that consume large quantities of water is an effective way of reducing water demand. Faced with the depletion of some of its coastal aquifers, Saudi Arabia enforced a ban on banana cultivation. However, this triggered groundwater-based banana cultivation in adjacent coastal Yemen (see picture).

Groundwater-based banana cultivation in coastal Yemen after ban in Saudi Arabia

Andhra Pradesh, India

Anantapur is the driest district in Andhra Pradesh State in India. In several villages farmers voluntarily imposed a ban on paddy cultivation in the dry season. The ban was implemented to prevent the lowering of groundwater levels which had caused water shortages at the end of the dry season.

Regulating pumping
Perugia Province, Italy

The Committee for the Protection of the Fergia River in Italy's Perugia Province dropped its opposition to a new concession for the Rocchetta mineral-water bottling company, but it was still fighting a decision by the regional council to allow industries to draw groundwater from the wells of Corcia and Rigali. The committee was to decide on a number of measures to conserve water including: strict limits on the amount of water that can be withdrawn, including a limit of seven litres per second in the dry months of August, September and October; the installation of monitoring equipment in every well to measure extraction and changes in the water table level; and using fees from Rocchetta to help pay for environmental protection projects along the river.

Safeguarding recharge by controlling sand mining
Anantapur, India

Sand and gravel are mined from river beds to be used for construction purposes. Yet the removal of sand and gravel severely limits the capacity of rivers to recharge groundwater and buffer floods. Several villages in Anantapur in India succeeded in preventing visiting trucks from sand mining by excavating a trench. Because of the trench, trucks could no longer enter the riverbed to remove the building material. Also guards were employed locally to prevent illegal entry.

Sand mining in the river bed, Anantapur, India

Restrictive local groundwater management practices

In Pakistan local groundwater is managed through informal committees which implement bans on dug wells or have well spacing rules and zoning. In India local groundwater is managed by local government officials or religious leaders who impose bans on drilling boreholes, promote local recharge measures, encourage water-saving strategies and regulate the use of wells. A water user association in Egypt is managing a common network and imposes a ban on new wells and in Yemen a drinking water committee has implemented zoning and a ban on agricultural wells.
These examples demonstrate that it is possible to set up functional organizations and promote new rules and norms on groundwater use. Scaling up is important and can be achieved for instance by systematically incorporating the promotion of local groundwater management into watershed improvement or rural drinking water supply programmes. The use of local fairs in which different organizations share their experiences in groundwater regulation and promoting water saving is also an effective mechanism to scale up groundwater use.

Reducing agricultural water demand

Simple techniques can be used to reduce the demand for water. The underlying principle is that only part of the rainfall or irrigation water is taken up by plants, the rest percolates into the deep groundwater, or is lost by evaporation from the surface. Therefore, by improving the efficiency of water use, and by reducing its loss due to evaporation, we can reduce water demand.
There are numerous methods to reduce such losses and to improve soil moisture. Some of them are listed below.

- Mulching, i.e., the application of organic or inorganic material such as plant debris, compost, etc., slows down the surface run-off, improves the soil moisture, reduces evaporation losses and improves soil fertility.
- Soil covered by crops slows down run-off and minimizes evaporation losses. Hence, fields should not be left bare for long periods of time.
- Ploughing helps to move the soil around. As a consequence it retains more water thereby reducing evaporation.
- Shelter belts of trees and bushes along the edge of agricultural fields slow down the wind speed and reduce evaporation and erosion.
- Planting of trees, grass, and bushes breaks the force of rain and helps rainwater penetrate the soil.
- Fog and dew contain substantial amounts of water that can be used directly by adapted plant species. Artificial surfaces such as netting-surfaced traps or polyethylene sheets can be exposed to catch water from fog and dew. The collected water can be used for crops.
- Contour farming is adopted in hilly areas and in lowland areas for paddy fields. Farmers recognise the efficiency of contour-based systems for conserving soil and water.
- Salt-resistant varieties of crops have also been developed recently. Because these grow in saline areas, overall agricultural productivity is increased without making additional demands on freshwater sources. Thus, this is a good water conservation strategy.
- Transfer of water from surplus areas to deficit areas by inter-linking water systems through canals, etc.
- Desalination technologies such as distillation, electro-dialysis and reverse osmosis are available.
- Use of efficient watering systems such as drip irrigation reduces the water consumption by plants.

Easy Ways to Conserve Water can also be found on the internet site of the Groundwater Foundation (www.groundwater.org).

3.2 WISE WATER USE

3.2.1 REDUCING CONSUMPTION IN RURAL AREAS

There are several methods which reduce groundwater consumption drastically. Often, even in areas where there is severe overexploitation, these measures are not or only partially applied. Particularly in agriculture there is considerable scope to save water. At this stage, however, a distinction needs to be made between water savings at farm level and at basin level. Overuse of groundwater at farm level may not be completely lost, as it will recharge the aquifer and still be available at basin level.

Land levelling to improve irrigation efficiency and reduce groundwater use
Mexico

Land levelling with laser technology has gained popularity amongst farmers. This new technology enables farmers to level their land very precisely, thereby improving field irrigation effectiveness and efficiency. Levelling the fields reduces losses of inputs such as fertilizer, ensures a better distribution of water in the fields and improves the overall crop performance and production.

Micro-irrigation
Israel

Due to the water scarcity in Israel it has been necessary to incorporate water-saving methods in agriculture. One of the methods used in Israel is micro-irrigation, also known as drip irrigation. Water is applied drop-by-drop at a grid just above the soil surface or using a subsurface system where water is applied below the surface through drip irrigation lateral tubes. Micro-irrigation saves water because the size of the wet soil surface decreases, consequently the amount of direct evaporation also decreases. Furthermore, there are no water losses due to wind. The first commercial factory ever producing drip irrigation equipment was opened in Israel by Netafim (see also box on micro-irrigation).

Drip irrigation lines, Ethiopia

Sprinkler irrigation, Mexico

Irrigation scheduling
Western United States

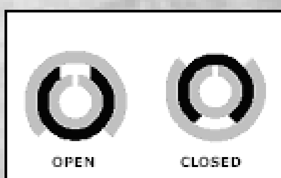
The Ogallala aquifer is the water source for western Kansas, southern Nebraska, northern Oklahoma and eastern Colorado. Since there is low precipitation and high evapotranspiration, groundwater recharge is negligible throughout the area. Due to over-abstraction in the area many wells have already gone dry. Irrigators started to recognize that they can play an important role in saving water to stop the Ogallala aquifer from further

Low-cost micro-irrigation techniques

Spray-head irrigation
Connected to a pedal, treadle or small petrol pump and mounted on a lay-flat hose, a spray-head is a good intermediate option between a watering can and more sophisticated sprinkler or drip irrigation. With high water use efficiency, low energy requirements and labour inputs, the spray irrigation technology has spread spontaneously from farmer to farmer in various West African countries. A recent survey showed that more than 60% of the market gardeners in Bamako, Mali used this method. The cost for a spray-head ranges between 2 and 5 US$, an optional petrol pump unit costs 300-600 US$.

Pepsi drip irrigation
Drip irrigation reduces water consumption but conventional drip technology is "high-tech" and expensive. The pepsi and nica drip irrigation systems offer simplified low-cost alternatives for small farmers. Using plastic which is usually used to package ice-popsicles, farmers in India developed drip line hoses, useable for one cropping season. The capacity of one of these systems ranges from 0.1 to 2 ha and the costs amount to 60 US$. Such a low cost system is not a risk for poor families to invest in it.

Nica drip irrigation
The Nica drip irrigation system consists of a hose in which holes are pierced at regular specified distances. These are covered with two cut-open pieces of the same hose (see cross sectional diagram) which can be opened or closed. The drip system can only be used on flat land but already operates at 0.5–1.0 m head of water. The initial estimated costs/ha are 300–600 US$, depending on crop and material used.



Source: Netherlands Water Partnership. 2006. 'Smart Water Solutions. Examples of innovative, low-cost technologies for wells, pumps, storage, irrigation and water treatment'.

depletion. Nowadays, they are adopting a wide assortment of water-saving practices including irrigation scheduling. With irrigation scheduling, irrigators determine the correct frequency and duration of the watering. The Mobile Irrigation Lab developed a programme called KanSched which serves as a tool to help with irrigation scheduling and field water management which in the end will conserve water from the Ogallala aquifer. KanSched can be found on the homepage of the Mobile Irrigation Lab (www.oznet.ksu.edu/mil).

Watering on even or uneven days
California, USA

In Fresno a schedule has been made which allows farmers to water on even days or on uneven days. This schedule is controlled by a third party. Farmers that deviate from the schedule are fined.

Changing cropping patterns to reduce groundwater use
Mexico

Farmers that are faced with lowering groundwater tables and problems of over-exploitation of groundwater resources have changed the cropping patterns from the traditional production of wheat (four irrigation turns) to barley (three irrigation turns), chick peas (two irrigation turns) and canola (one irrigation turn). Farmers producing fodder crops have changed from alfalfa production to fodder maize. Changing the crops and their crop water requirements lowers the water demand and consequently the necessity to abstract groundwater.

Using mulch material

The use of mulch is widel spread all over the world. Organic or inorganic mulches offer a wide range of possibilities for modifying the surface characteristics, reducing wind or water erosion, and the crop microclimates. The mulches keep the soil either cool or warm and reduce evaporative losses. A wide variety of materials is used for mulching.
Organic: Leaf mulches, crop residue, coir pith (blocks made of fibre obtained from the husk of a coconut), woody material and straw mulches (in combination with termite activity), grass mulching, manure.
Inorganic: Layers of rock, gravel, pebbles or sand are spread over fields or piled around individual plants leaving the space between open for cultivation, black volcanic lapilli (volcanic ashes), plastic covering, or rubber mulch made from car tyres.

Conservation tillage and mulching

A closely related and highly effective method of managing soil moisture is conservation tillage. A range of methods are used in conservation tillage, such as pre-rain ploughing (to have more effective infiltration) and subsoiling (to break the plough pan and allow deep infiltration). Mulching or planking is also promoted, whereby after ploughing the clay clods are broken and the soil pores are closed by moving a plank or beam across the soil.

Vermi-compost (worm compost)

Organic waste can be turned into compost using earthworms (known as vermi-compost). When the compost is mixed with top soil, it improves soil moisture retention capacity. Vermi-compost also increases water holding capacity, reduces salinization and erosion, enhances soil productivity and induces resistance to pest and disease attacks. Vermi-compost can be easily made by using a container which keeps light out and moisture in. The container has aeration holes in the lid and covered drainage holes at the ottom. Once the contraption is ready, common red wiggler worms (available at bait shops) can be purchased and they can start processing domestic organic waste.

Mulching in Pakistan. The topsoil is levelled and closed with a heavy wooden beam.

Reuse of water for irrigation
Oregon, USA

Reuse of irrigation water is fairly common practice in the USA. The nature and amount of reuse depends on local conditions. Not all waste water can be used: water quality can decrease to the point of making it unsuitable in instances when there is high sediment or dissolved chemical load. In Oregon the opposite happens and waste water quality is managed in such a way to take advantage of available nutrients. Pumped groundwater is analysed to determine whether it is deficient in nutrients for certain crops. Only if these are lacking the nutrients can be added accordingly. For example, if the concentration of nitrogen is below 25 mg per litre then extra nitrogen is added to meet the crop's requirements.

Water savings in and around the house

Water shortages are only set to become a larger problem in the future. Domestic water is an expensive commodity as it has to be treated, frequently tested and distributed to every home. Moreover, heating water requires a lot of energy. Simple and innovative water and energy savings are summarized below.

Indoors:

- Adjust the washing machine level to the size of the load of laundry. If you can't adjust your machine's wash level, try to wash only full loads.
- Reduce showering time.
- Collect excess running water while you are waiting for hot water in basins or buckets and use it to water plants.
- Wash only full loads of dishes in dishwashers.
- Fill a basin with water for rinsing vegetables or washing dishes instead of letting the faucet run. When finished, don't dump the water out — use it to water plants.
- Fix all leaking faucets, shower heads, and toilet tanks.
- When shaving, fill the sink basin with water instead of leaving the faucet on.
- Install low-flow showerheads and faucet aerators.
- Install a toilet cycle diverter and/or displacement device in the tank.
- Replace an older model toilet that uses a large flush volume with a lower six litre flush volume model.

Outdoors:

- Reduce watering frequency to once every five days and water thoroughly – 2.5 to 5 cm at a time to encourage deep root growth. Apply only what your garden needs to survive, don't overwater. If it rains 25mm or more, wait at least five days to water.
- Collect rainwater for washing your car and watering the garden.
- Water in the early morning or evening hours - not during the heat of the day.
- Use a sprinkler that produces large drops of water instead of a mist, or use a drip system - do not water on windy days.
- Mulch trees and plants to retain moisture and prevent evaporation.
- Use water-wise plants (xeriscaping) for landscaping.
- Cover swimming pools to reduce evaporation when not in use.
- Minimize emptying and/or refilling of pools.
- Wash cars by filling a bucket and turning off the hose. One can also use a spray nozzle that only emits water when squeezed.
- Sweep sidewalks and driveways with a broom and muscle power instead of using the hose.

Source: www.fayettecountygroundwater.com/conservation.htm and www.kampenhout.be/gemeente/milieu/duurzaam-water.html

3.2.2 WATER SAVING IN URBAN AREAS

Xeriscape

Texas, USA

In Texas there is insufficient natural rainfall to meet the water demand of different ecosystems. A concept called Xeriscape, which conserves water and protects the environment, is used in the state. The concept is based on seven principles: planning and design, soil analysis and preparation, practical turf areas, appropriate plant selection (usually indigenous low-water consuming species), efficient irrigation, use of mulches and appropriate maintenance. Tables are made to demonstrate what kind of groundcover can be used in different areas of Texas (see figure).

Groundcovers

Common name	Scientific name	Best adapted for	Exposure	Notes
Ajuga	*Ajuga reptans*	7	Shade	Variety of foliage colors and blue flowers; requires well-drained soil
Asiatic jasmine	*Trachelospermum asiaticum*	1,2,3,4,6	Sun/shade	Evergreen: green or variegated foliage
Confederate jasmine	*Trachelospermum jasminoides*	1,2,3,4	Sun/shade	Evergreen; fragrant, white spring flowers
English ivy	*Hedera Helix*	7	Shade	Evergreen; green or variegated foliage
Liriope	*Liriope muscari*	7	Sun/shade	Evergreen; grass-like foliage; purple blooms; varieties: big blue, gigantic
Monkey grass	*Ophiopogon japonicus*	7	Sun/shade	Evergreen, grass-like foliage; dwarf and standard varieties
Prostrate rosemary	*Rosmarinus officinalis*	2	Sun	Grayish-green, fragrant foliage; light blue flowers
Santolina	*Santolina sp.*	3,4,5,6	Sun	Species with green or silver foliage
Trailing juniper	*Juniperus sp.*	3,4,5,6	Sun	Several varieties available; not suitable for wet, humid areas
Vinca	*Vinca major*	7	Shade	Blue flowers and dark green foliage

Detecting leaks with geophones

Losses in piped water supply systems can have significant costs as there is a need for increased pumping, treatment and additional operational investment. Lately many utilities are developing methods to detect, locate and correct water main leaks. An example of a new method for detecting leaks is with geophones (in the picture used by a student at West Virginia University). Geophones work in a similar way to stethoscopes and are inexpensive.

Geophones used to detect water leaks in piped water supply systems in West Virginia, USA

3.3 USING ECONOMIC INCENTIVES

In addition to promoting water-saving measures and local regulation, economic incentives are used to change water users' behaviour and encourage corrective measures. These economic incentives are in addition to normal price mechanisms that are not able to balance resource use. As long as it is relatively cheap to pump groundwater, however precious and scarce, overuse is bound to take place.
Economic incentives work at various levels – at economic regulation in the country, for instance in import and export policies – as well as influencing pricing systems through subsidies and penalties. The table gives an overview.

Main policies affecting price incentives	
Trade policies	Regulation of export and import of high and low water consuming crops
Public investment policies	Public investment in water resource infrastructure: ▪ Surface water storage and diversion ▪ Groundwater extraction facilities ▪ Water conservation measures ▪ Recharge and reuse facilities
Crop pricing policies	Pricing controls on different crops Government procurement of agricultural crops
Agricultural input policies	Pricing and policies on availability of major agricultural inputs, such as seeds, fertilizer, pesticide, tractors
Energy pricing	Pricing of electricity and diesel (including control on black market or pilferage) Effective collection of bills Structure of energy pricing (flat rates or consumption-based rates)

Main policies affecting non-price incentives	
Rural and peri-urban infrastructure policies	Public investment in roads, drinking water supply, agro-processing and link to water management
Groundwater governance and regulation	Implementation of Water Law and complementary regulation
Policies supporting local regulation	Sharing of information on aquifer characteristics, effectiveness of awareness and education programmes, policies on land and water rights, particularly as they relate to run-off rights and to groundwater use
Promotion of business climate	Promotion of private sector supply in water-saving technology
Policies affecting water markets	Availability of group or individual credit, rules on right of way, promotion of high-capacity well systems, direct promotion of water sharing
Policies on crop diversification	Attention to crop choices and water conservation in agricultural research, extension and demonstration programmes

Main policies affecting price and non-price incentives

Economic incentives to improve nitrogen management and reduce leaching
USA

The Lower Salt Creek Ground Water Reservoir Advisory Group was established in 2002. This group assisted in developing incentive programmes to implement best management practices that improve nitrogen management and reduce leaching which leads to better protection of groundwater. The incentives that are still in practice are:

- 75% cost-share for a fertilizer flow meter
- 100% cost-share for a vertical dam manifold and hoses
- 75% cost-share for a water well flow meter and moisture probe
- 75% cost-share for soil sampling
- 75% cost-share for establishing irrigation water best management practices

Tax incentives for constructing impoundments
Arkansas, USA

The Arkansas Natural Resources Commission has set up a programme to encourage water users to invest in:

- Constructing impoundments to use available surface
- water and at the same time decrease their dependence on groundwater
- Conversion from groundwater use to surface water use
- Land levelling in order to reduce the use of water for irrigation

For these three options an income tax credit is available. By filling in application forms on the website of ANRC (www.anrc.arkansas.gov/TaxIncentives.html) one can apply for any one of these incentives.

Subsidy for diverting run-off from impermeable surfaces to the sewage system
Nijmegen, The Netherlands

In Nijmegen in the Netherlands, the city mainly consists of impermeable surfaces such as tarmacked streets. When it rains the water is transported from the paved surfaces to the storm sewage system. But when rainwater is transported to an infiltration area, groundwater is naturally recharged thereby preventing the storm sewage system from overloading. In Nijmegen the local government together with the Rivierenland Water Board provides a subsidy of 4.55 Euro for each m^2 of impermeable surface.

Public Private Partnership (PPP) substituting for groundwater
Guerdane, Morocco

The Guerdane area in Morocco used to be irrigated by groundwater but the future of the highly productive area was in jeopardy, when groundwater resources were depleted. To compensate for the disappearing groundwater resources a surface irrigation system was developed using a PPP formula.

Under a conventional approach the state would have pre-financed all investments assuming it would recover 40% of the construction costs from farmers over 20 years. In reality, recovery rates are much lower (closer to 20%) in comparable projects. The operation would be carried out by the State – usually with unsatisfactory performance, continued reliance on subsidy and perennial under-funding.

An alternative approach was considered, centred around a Public Private Partnership. Although the government would remain the

Value of groundwater and water pricing and EU's Water framework directive

Historically, groundwater has been priced well below its value and, as a consequence has been misallocated. In many countries, no charge is imposed for water withdrawals, and the consumer, whether a public water supply entity, an individual, or a firm regards the cost as being confined to the energy used for pumping, the costs of well construction, treatment and distribution systems. As a result, depletion and pollution continue because it is not recognised that groundwater has a high or long-term value. Policies which are being currently developed often prohibit additional groundwater uses (and users in certain areas, making abstraction licences marketable) but are often fail to regulate current groundwater users.

Although much work needs to be done in this area, the EU's Water Framework Directive prescribes the principle of cost recovery of water services. Applicable to both surface water and groundwater, the directive requires Member States to take account of the principle of recovery of the costs of water services, including environmental and resource costs. 'Recovery of the costs' is determined through an economic analysis of water services based on long-term forecasts of supply and demand for water in the river basin district. The 'polluter pays principle' is also taken into account. Notably the EU Framework Directive steers clear of 'full cost pricing' as most people are more amenable to the sound of full cost accounting and full cost recovery.

asset owner, contracts were put out to a private party in order to provide the operation of the irrigation canals. The willingness to pay for surface irrigation among farmers was high, as it meant the survival of their citrus groves.

A public service delegation contract for thirty years was to be given out. The private operators were expected to bring in 43%, whereas the government supported the project for 28% and a concessionaire loan for another 28%. The government investment allows the water fee to be on a par with current groundwater pumping costs. The supply risk of the project was covered under an arrangement whereby the government undertakes to compensate the service provider for any water deficit of more than 22.75%. Water users that were interested in being connected had to subscribe. The private operator was not supposed to start until subscriptions reached 80% of the project water allocation.

The PPP was then tendered and special efforts were made to encourage Moroccan contractors. The service providers were responsible for the project design. The contract with the service provider indicated a limited number of technical criteria for guaranteeing good service quality and minimal environmental impact. Evaluation of the bids was on the basis of proposed users' contribution and irrigation water price per m^3. The consortium that won the contract (a Moroccan company with French irrigation companies in the group) was able to provide its services at a connection fee of DH 8000/ha and a price of 1.48 DH/m^3. The PPP option in all respects was better value for money than the state-operated or water user-operated packages.

Sustainable land use in order to keep aquifers clean
France

Vittel is one of the largest bottlers of natural mineral water. The most important sources of water are situated in France. These areas are in heavily farmed watersheds. Nutrients and pesticides used by farmers contaminate the aquifers of Vittel's sources. Vittel calculated that purchasing farmland, reforesting sensitive infiltration zones and stimulating farmers to switch to organic farming was more cost-effective than building infiltration plants. Vittel could offer farmers profitable prices for their participation. The company has purchased 1500 ha of farmland above market price. Farmers share profits from the land they have sold and they also receive an annual payment per hectare in order to manage the land in a sustainable way.

Inducing water pricing policy
Port Elgin, Canada

In 1991, the municipality of Port Elgin, Ontario, decided to install 2,400 residential water meters at a cost of Canadian $550,000 instead of building a $5.5 million expansion of the local water treatment plant. Consequently, in 1993 there was a reduction of summer water use of 50% by the year 1993, and an overall reduction of 25%, and the municipality saved $12,000 in sewage treatment operating costs.

Rationalizing flat tariff charges on electricity consumption
India

India has the highest estimated groundwater use in the world (see figure in chapter 1), with 40% of agriculture dependent on groundwater use. Surveys have shown that subsidies on electricity encourage overuse as farmers tend to run their pumps 40%-250% longer than those farmers who buy diesel at market rates to run their pumps. However, converting the power sector's 'conventional' flat-rate tariff to one using electricity metering would be difficult. The installation of meters on the 14 million scattered rural pumps would have to overcome numerous barriers such as meter-reading, billing, collecting charges and ensuring buy-in from farmers.

Many farmers are suspicious of installing meters on their water pumps after their experience with corrupt meter readers in the 1980s. The alternative strategy is to supply farmers with a restricted annual high quality supply of farm power; matching the supply with peak periods of moisture stress. If well managed, such a strategy could cut the wasteful use of groundwater by 12-18 km^3 of water/year in western and southern India, as well as reduce power expenditures by US$ 0.8 to 1.2 billion and improve farmers' satisfaction with the power industry.

Buying water rights to reduce aquifer over-exploitation
Mexico

Federal Governments in central Mexico established funds to buy water rights from farmers. These water rights are bought from farmers that willingly relinquish their water rights. In this way pressure on heavily used aquifers is mitigated.

Selling water to cities
Tamil Nadu, India

Farmers in peri-urban areas in Tamil Nadu have been able to sell the water they abstract from wells to water vendors in large cities. As the city of Chennai is rapidly growing, farmers have found that selling their groundwater is profitable. As the monetary value of water exceeds the income from crops, farmers with available sources resort to selling their water. State laws prioritize domestic use above agricultural use, therefore during droughts, there is more pressure on available water resources being diverted and sold to the urban areas. Although the practice of selling water enables some farmers to diversify their income generating activities, there are also some farmers who are now forced to buy water to irrigate their crops.

Payment for the provision of environmental services
Pimampiro, Ecuador

In an attempt to counter the degradation of highlands and enhance the groundwater recharge area (thus improving urban and irrigation water availability) the municipality of Pimampiro piloted and enacted payment for the protection of the upstream catchment area. Residents in Pimampiro were required to make a payment of 20% of their water consumption rate.
The area of Nueva América, consisting of 638 ha of forests and high altitude grasslands, was considered to be the source of important groundwater sources for the municipality. Land owners in Nueva América received payments for the protection of their grassland and forest areas amounting to 1$/month/ha if the land was kept idle and 0.5$ /month/ha if there were activities such as farming. The project was a pioneering experience from which the lessons can be used to inform further payment schemes in Pimampiro as well as future projects in other areas.

Energy pricing coupled to water rights
Mexico

The Mexican government through the Federal Electricity Commission (CFE) has established an electricity tariff that is coupled to the groundwater rights of the users. The electricity use that falls within the water rights gets heavily subsidized; all energy above the concession volume has no subsidies. It established a new single-rate tariff of US$ 0.0316 per kWh called 9CU that links groundwater extraction to the energy supply. Normatively, to acquire this electricity rate users need proof of a valid concession title and an Annual Energy Limit (AEL) in KWh/yr is established for each well (see box below for AEL formulation).

Annual Energy Limit (AEL)

The AEL is calculated by:

AEL= 438 + KVC/e

where 438 is the lighting requirement for the well shed, K = 0.0026 (a unit conversion constant), V the annual CNA concession volume (m^3), C the dynamic lift equal to the depth of the bore in meters as authorized in the concession title and e with a minimum of 0.52; the electromechanical efficiency of the pump-motor set. Users exceeding this AEL pay for the excess energy according to the regular 9 and 9M tariff.

Tariff	Consumption			
	1-5000 kWh	5001-15000 kWh	15001-35000 kWh	>35000 kWh
9 Low tension	0.0316	0.0349	0.0383	0.0419
9M Medium tension	0.0316	0.0354	0.0386	0.0422

Electricity supply and bore well, Guanajuato, Mexico

Separating agricultural from non-agricultural electricity feeders

Gujarat, India

By separating agricultural electricity feeders from non-agricultural ones, the Jyotigram scheme in Gujarat created the basis for farm power rationing in the countryside. Gujarat is notorious for groundwater over-exploitation. Energy subsidies for groundwater irrigators had induced groundwater over-draft and had left the state with a bankrupt electricity utility and depleted aquifers. Efforts to charge a rational electricity tariff for groundwater irrigators were unsuccessful. The Jyotigram Scheme ensured that villages get a 24 hour three-phase power supply for domestic uses, schools, hospitals, village industries, subject to metered tariff. Tube-well operators get 8 hours/day of power at full voltage according to a pre-announced schedule.

4| PROMOTING RECHARGE

Well in sand river in Sheeb, Eritrea

This chapter discusses measures to improve groundwater supply. Such measures are best embedded in regulatory measures, as outlined in the preceding chapter. There are several well established measures to enhance groundwater availability through managed recharge. A main challenge is to reach scale in water harvesting, moving away from individual measures with only very localized impact. The challenge is to reach density so as to make a substantial impact on local water retention. There are several inspiring examples of areas that were 'turned around', such as the Loess Plateau in China or the Kitui Area in Kenya. Once scale is reached, scale will sustain. At the same time it is important not to jeopardize natural recharge processes.

Kanda System. Run-off is collected in a cistern hewn from mountain rock, Afghanistan

A consideration often raised is the effect of intensive managed recharge on downstream areas. However, even where recharge measures are implemented at scale, they usually only capture a small part of total run-off. In Kitui in Kenya where a large a number of measures were implemented including five-hundred sand dams, the proportion of run-off captured was an estimated 3% only. This 3% however made all the differences locally however in terms of improved livelihood: availability of water for domestic use, livestock, small scale industry and agriculture. There is a need for ambitious drought proofing and recharge programmes to rehabilitate regional water systems and adapt to climate variability and climate change.

4.1 SAFEGUARDING NATURAL RECHARGE CAPACITY

In many areas the natural capacity to store rainfall in a basin is impaired by uncontrolled development and pressure. A major threat is sand and gravel mining for building materials. The removal of sand and gravel from rivers reduces the capacity of rivers to store water and recharge shallow aquifers. Where the river is depleted of its natural storage material floods will not be attenuated. They may rush down and create havoc. The same occurs when wetlands are converted. As long as wetlands are intact, they store excess water and feed aquifers and serve as flood buffers, in addition to a variety of other functions. The more general point is that the natural storage capacity in a basin should be carefully managed. Drastic change to the natural drainage network – dissecting drains, paving large stretches – alters the capacity to retain and storage water. When drains become deep by gullying, they will tend to draw down groundwater levels over a large area.

The value of wetlands in restoring groundwater levels
Wetlands, Nigeria & USA

The Hadejia-Nguru wetlands in northern Nigeria play a major role in recharging aquifers that are used by local people for domestic water supplies. The value of these domestic water supplies has been recently estimated at US$ 4.8 million per year underlining the importance of the wetlands role. Likewise in Florida a 223,000-hectare swamp has been valued at US$ 25 million per year for its role in storing water and recharging the aquifer. However, in a lot of areas around the world, groundwater abstraction and other interventions threaten the existence of wetlands (see also box on 'Groundwater and wetlands in brief').

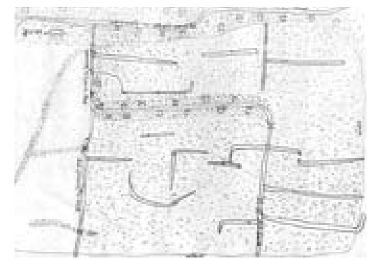
Wetland in the Terai, Nepal

Reactivating the flood plains
The Netherlands

Following the near floods of 1995, water management policy in the Netherlands was rethought. One new concept was to create more space for the rivers, so as to improve their capacity to store flood peaks. As a result some of the smaller dikes were dismantled and the flood plains were restored. This served a second purpose besides flood management. By restoring the flood plain and even constructing trenches and side channels in them it was also expected that more groundwater would be recharged.

Wet watershed management
North Bengal, India

With an annual rainfall between 2200 and 3500 mm, most of which is concentrated in the monsoon period (May-September) the Terai region of North Bengal is one of the wettest places on earth. During this wet period the coarse subsoil quickly absorbs the water; low-lying areas are only temporarily inundated and large quantities of water are drained away through gullies and as sheet flows.
However, by improving drainage patterns, the run-off can be slowed down and water can be retained. This avoids the loss of the thin fertile topsoil and improves the reliability of cultivating rain-fed paddy. Wet watershed management, which is essentially a series of landscaping measures (bunds and plugging) to break the speed of run-off, spreads water over larger areas and aims at avoiding deep surface drainage by plugging gullies. In an evaluation these works confirmed the extremely high return of investments as cropping intensities increased from 90% to 201%.



Wet watershed management. Improving drainage patterns, India

Groundwater and wetlands in brief

Many wetlands help recharge underground aquifers that store 97% of the world's unfrozen freshwater.

The recharge function of the Garet El Haouria wetland in Tunisia depended upon winter flooding. Drainage canals to control the flooding removed this wetland's recharge function; moreover water abstraction from wells in the area for irrigation of citrus orchards and market gardens dramatically altered the hydrology of the area. Groundwater levels fell by 9 m between 1980 and 1995 and some wells have been abandoned because of saltwater intrusion. Channelling water back towards the wetland area could help raise the groundwater tables.

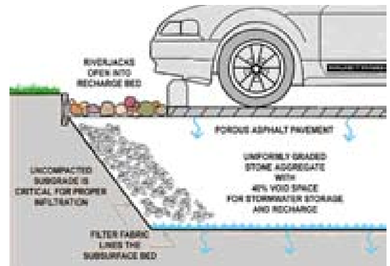
In some situations the direction of flow of water between wetland and aquifer depends upon the prevailing conditions. For example, in some swamps in Belarus the wetlands recharge the aquifer when the water table is low, but the aquifer will recharge the wetland when the water table is high.

Porous pavements

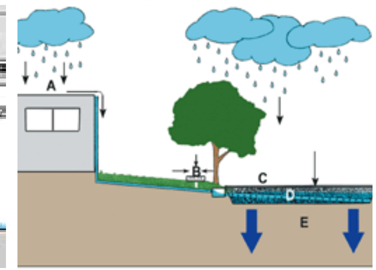
North Carolina, USA

Porous pavements prevent rainwater disappearing from an area without being able to infiltrate. The first large porous pavement parking systems in North Carolina were introduced in 2002. The built-up area of the University of North Carolina (UNC) increased, causing an increase in the volume and peaks of run-off water. Moreover, water quality degraded as natural filtration no longer occurred.
By using porous pavements, for example at parking lots, the rainwater is allowed to pass through the pavement. In this case porous asphalt was used. The difference between porous asphalt and conventional asphalt is the concentration of fines. By using fewer fines, the asphalt becomes porous. Underneath the asphalt there is a stone recharge bed consisting of a clean-washed, uniformly graded stone mix. The run-off water which infiltrates into the stone aggregate contains pollutants thus the water infiltrating into the subsoil first goes through a filter fabric, which lines the subsurface bed.

At UNC water is also collected from the roofs. Since this water is relatively clean and sediment-free, the UNC connects the roof leaders directly to sub-surface storage.



Porous parking pavements



Roof leaders used at North Carolina University, USA

Roof leaders can be connected directly to the sub-surface infiltration bed:

A - Precipitation is carried from the roof by roof drains to storage beds.
B - Stormwater run-off from impervious areas and lawn areas is carried to storage beds.
C - Precipitation that falls on pervious paving enters storage bed directly.
D - Stone beds with 40% void space store stormwater. Perforated

pipes distribute stormwater from impervious surfaces evenly throughout the beds.

E - Stormwater exfiltrates from storage beds into soil and recharges the groundwater

Divert stormwater from the sewage system

De Vliert, The Netherlands

As urbanization progresses in many countries stormwater often disappears directly in the sewerage system. This forecloses the opportunity for recharge and moreover overloads the water treatment facilities. A novel system was used in "De Vliert" in 's-Hertogenbosch in the Netherlands. A separate system was put in place to remove the stormwater, a so-called infiltration system. This system captures the water and slowly emits the water to the soil. In this way, the stormwater stays in the same area and recharges the groundwater rather than being quickly evacuated to the river system.

Flood water disposal and recharge

Orissa, India

In Orissa, India, drainage, flood management and recharge were combined. Road engineering, drainage design and flood management were integrated to create a system, consisting of an escape from the main drain, falling into the subdrain where eventually a lowered portion of the road acts as the spillway of the subdrain. At high flood levels, water is diverted to a retention area (see also photo) enabling recharge of groundwater.

Combining flood management and recharge using the road as a spillway in Orissa, India

Control invasive species

Some invasive species consume large quantities of groundwater. An example is the *Chromolaena Odorata* that has spread in several savannah tracts of Africa.

Carefully plan hydraulic works

Tihama, Yemen

Several hydraulic works in the Tihama Plain in Yemen were built to control surface water, i.e. weirs and bed stabilizers. These were built on the bed rock but by doing so they also blocked the subsurface flow in the dry ephemeral rivers (wadis). This causes water to rise upstream of the structures, but wells to dry up downstream of these structures.

4.2 MANAGED AQUIFER RECHARGE

Although water harvesting and artificial recharge have been applied in many areas, in recent years there has been a rapid global increase in managed aquifer recharge. There are various types of recharge techniques, either through capturing rain or rain run-off or by importing water from elsewhere. Each area has a best fit depending on natural conditions (slope, soil, rainfall patterns) and local knowledge and traditions. It is often important to promote those techniques that can be adopted by private families and local investors, so as to upscale water harvesting and artificial recharge.

Percolation tanks

Maharashtra, India

A percolation tank is a structure that is usually built across streams and gullies to collect rain run-off. The water collected in the tank slowly seeps away to the groundwater. In Maharashtra the use of percolation tanks for recharging groundwater is very common. It is estimated that over 8,000 percolation tanks have been installed.

Leaking ditch irrigation

New Mexico

In northern New Mexico acequias are part of a traditional irrigation system. An acequia is an irrigation ditch which transports water from a river or spring to a parcel of land. The acequias are under scrutiny because of their high seepage losses. These seepage losses however have many valuable functions, for example recharging shallow groundwater tables.
Another advantage of using acequias is the enhancement of riparian vegetation and wildlife habitat along the ditches.

Managed aquifer recharge systems

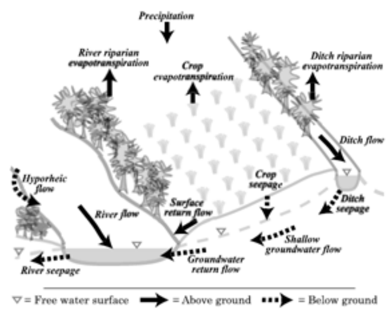
Techniques referring primarily to water infiltration

- Spreading methods: infiltration ponds and basins, flooding, ditches, furrows, drains, irrigation
- Induced bank infiltration
- Well, shaft and borehole recharge: deep-well injection, shallow well/shaft/pit infiltration

Techniques referring primarily to intercepting water

- In-channel modifications: recharge dams, sub-surface dams, sand dams, channel spreading
- Harvesting run-off: barriers and bunds, trenches

Source: www.igrac.nl



Interactions between surface water and groundwater along the irrigated corridor between an acequia and a river, New Mexico

Injection wells

Atlantis, South Africa

Atlantis is situated on the semi-arid west coast of South Africa. Average rainfall is 450 mm and there are no major surface water systems. Groundwater is the life-line and needs to be actively protected. For over 20 years an artificial groundwater recharge system has been in operation in Atlantis. From two well fields in the coastal aquifer groundwater is extracted. This water is treated, distributed, used, collected, treated and artificially recharged into the aquifer together with urban stormwater. To reduce groundwater salinity the system has been modified a few times. The total water recharge of the system is 2 million m^3 per year.

Las Vegas Valley, USA

Artificial recharge in the Las Vegas Valley is part of the Groundwater Management Program. Artificial recharge takes place from October to May. Treated water from the Colorado River is injected into the groundwater basin. Up to 6 million m^3 can be added annually, if required. Due to the recharge, water levels are stable and groundwater wells continue to function.

The Netherlands

The scope for storing water at depth in the Netherland was investigated by a foundation "Leven met Water".
Salinization, urbanization and peak precipitation are increasing in the Netherlands. As a result the need for freshwater retention is increasing. Storage of water at surface level however requires considerable space which is in short supply in the Netherlands. The study established that it could be feasible to store water in the aquifers during the winter months and extract it during the drier summer months. The water would be injected into a well which is connected to an aquifer 90-125 meters below surface level.

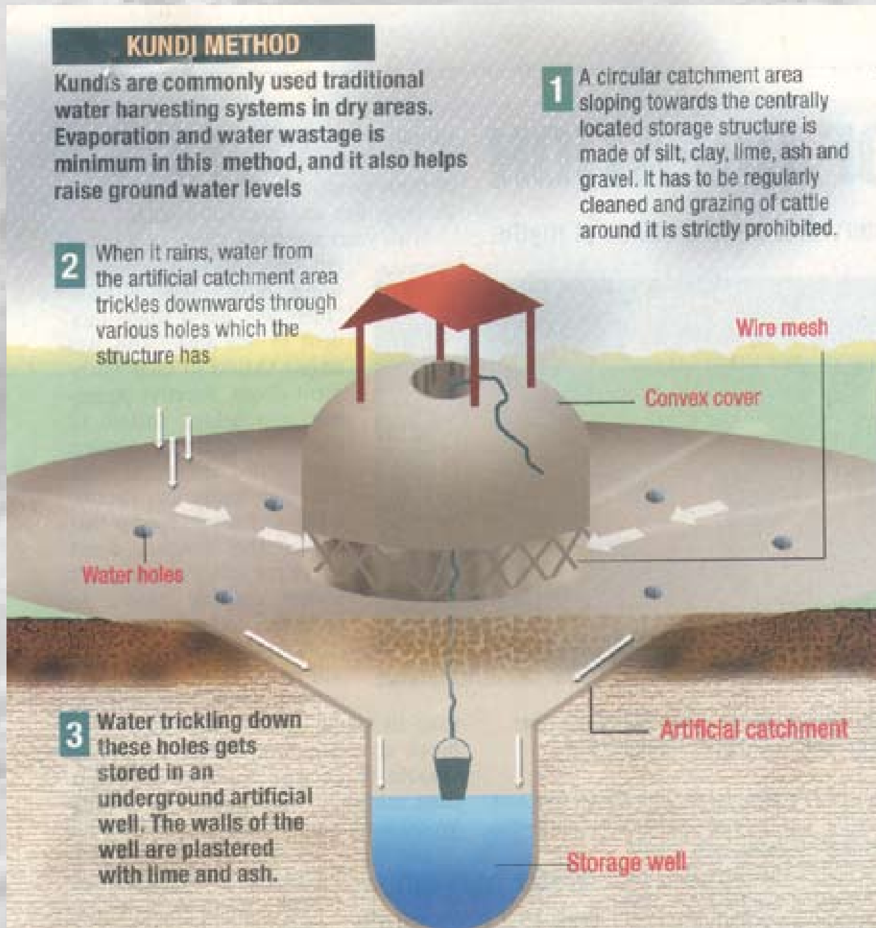
Contour bunds intercept the sheetflow and collect the water in the trench, from where it infiltrates, India

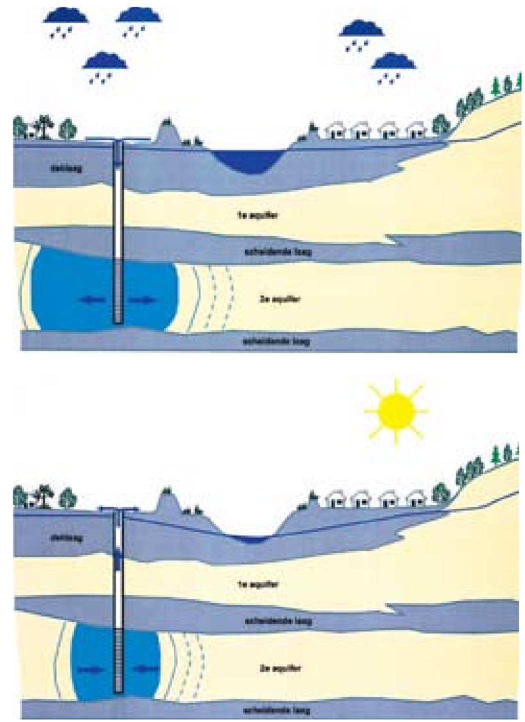
Maximize the potential of road infrastructure to contribute to recharge

Roads form unnatural obstacles in the landscape. They have an important effect on surface water hydrology. Dependent on their location across contour lines they can be the main feature guiding surface run-off. The location and size of culverts and other cross-drainage structure will influence where water is impounded and where it is recharged. Appropriate road planning and design can be one of the most effective means to ensure larger groundwater recharge in a basin.

Water harvesting along a road in Koshe, Ethiopia

The Kundi water harvesting technique in Neemi, Rajasthan - India

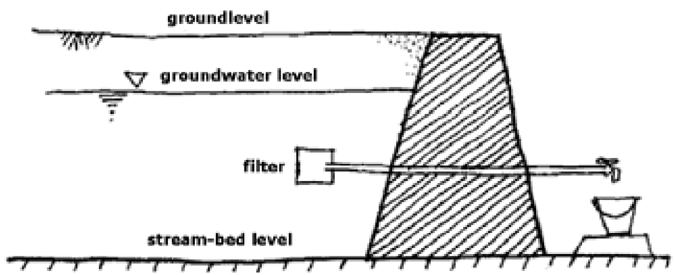




Storing water at depth, The Netherlands

Sand dams creating an aquifer
Kenya

A sand dam is a vertical barrier, made of concrete or masonry across a seasonal riverbed. The dam is built on an impermeable layer of bedrock to prevent loss of water to deep percolation. As sand dams are built in small steps, sand is deposited behind it and a small aquifer is created. Water is stored in this aquifer and is available throughout the year. The sand dam also raises the groundwater level in the entire area, improving moisture available for natural vegetation and rain-fed crops. In Kenya sand dams are common in Ukambani, Kitui, Tharaka and Mbeere districts.



Sand storage dam

Sub-surface dams
Swarnamukhi River basin, India

In the Swarnamukhi River basin most, if not all, of the rain falls during the monsoon season. The main objective behind the construction of sub-surface dams in the basin is to retain the base flow infiltrating into sandy alluvium and thereby to increase the groundwater potential for meeting future water demands. An analysis of hydrographs of piezometers of four sub-surface dams, monitored during October 2001–December 2002, revealed that there was an average rise of 1.44 m in post-monsoon and 1.80 m in the pre-monsoon period after the sub-surface dams were constructed. Further, the fluctuations of the groundwater levels in the range of 3.1–10 m prior to construction, were in stark contrast with the reduced fluctuations thereafter ranging from 0.4-3.1 m.

Siphons on recharge dams

In several countries artificial recharge dams have been built. A main constraint for such recharge dams is that the reservoir area is soon sealed with fine sediment, making it impossible for the stored water to percolate and recharge. This can be overcome by using siphons. The siphons will lift the clean water from the reservoirs and release it downstream in a recharge area.

Combining supply and demand measures
Batinah, Oman

Often a range of measures is combined to balance supply and demand. A number of measures were promoted to rebalance groundwater utilization in the Batinah coastal area in Oman. The measures included: the promotion of micro-irrigation, use of treated waste water for urban irrigation and the construction of rain water storage reservoirs. Over the years the area under micro-irrigation increased to 28% of the cropped area and 15 recharge dams were constructed. In spite of these measures, overuse continued and recharge dams made up only 15% of the deficit. Groundwater pumping continued to go up, because of increased vegetable cultivation and urban beautification programmes.

5| SAFEGUARDING AND IMPROVING GROUNDWATER QUALITY

Boy with symptoms of dental fluorosis in West Bengal, India

Safe groundwater is essential for public health. Low quality may be natural or may be caused by pollution. In managing groundwater quality, preventing point pollution (section 5.1) and minimizing non-point pollution (section 5.2) are crucial to safeguarding groundwater usability in the future. Measures may focus on vulnerable areas, in particular sources of drinking water extraction (5.3). In other cases treating low-quality groundwater is necessary (section 5.4). The last resort is the remediation of groundwater (section 5.5).

To assess what is 'safe' water quality, the WHO drinking water standards are the best guide. In many countries they have been adopted one-to-one, but in some cases norms have been adjusted to the country's capacity to manage water quality. An example is Tanzania, that adopted 8 mg/l as the norm for fluor, acknowledging that it was not possible to provide water according to the stricter norms.

5.1 AVOIDING POINT POLLUTION AND CONTAMINATION

Point pollution is a threat to groundwater quality. It can be caused among others by leaking underground storage tanks, leachate from dumps and landfills, industrial effluent or mining or road run-off. Point pollution is particularly dangerous close to urban centres, where it can irreversibly damage a vital resource.

WHO drinking water standards	
pH	Desirable: 6.5-8.5
Conductivity	250 microS/cm
Cations (positive ions)	
Aluminium (Al)	0.2 mg/l
Arsenic (As)	0.01 mg/l
Cadmium (Cd)	0.003 mg/l
Chromium (Cr)	0.05 mg/l
Copper (Cu)	2 mg/l
Iron (Fe)	Desirable: 0.3 mg/l
Lead (Pb)	0.01 mg/l
Manganese (Mn)	0.5 mg/l
Mercury (Hg)	0.001 mg/l
Nickel (Ni)	0.02 mg/l
Nitrogen (total N)	50 mg/l
Selenium (Se)	0.01 mg/l
Sodium (Na)	200 mg/l
Tin (Sn) inorganic	No guideline
Uranium (U)	1.4 mg/l
Zinc (Zn)	3 mg/l
Anions (negative ions)	
Chloride (Cl)	250 mg/l
Cyanide (CN)	0.07 mg/l
Fluoride (F)	1.5 mg/l
Sulphate (SO4)	500 mg/l
Nitrate (NO3)	(See Nitrogen)
Nitrite (NO2)	(See Nitrogen)

Introducing clean technology through industry associations
Pakistan

Groundwater pollution from the leather industry, especially by chromium, has been a major problem in several parts of Pakistan. In the 1990s, the Pakistan Tanners Association initiated the Korangi Environmental Management Programme (KEMP). The main objective of the programme was to reduce pollution from untreated effluents so as to comply with international European Union regulations. The programme initially targeted owners of 60 tanneries in the Korangi area, near Karachi. Under the programme, cleaner production methods and technologies were introduced, including laboratory improvements; conservation measures; physical improvements in drainage and chemical storage; and operational health and safety systems. Cleaner technologies include chemical recovery plants, primary treatment plants and mechanised solutions, such as salt de-dusters. Under the project 'free' technical advise was given with the consultants team being paid, once a tannery accepted the clean technology package. Following the KEMP's success, a similar programme was started in Pakistan's textile industry, in which 100 progressive textile mills are participating.

Laboratory established by industries

Primary treatment of tannery waste water

Secondary treatment of tannery waste water

Leather processing

Collecting excess chromium

Water samples

Groundwater protection code for petrol stations
United Kingdom

In the United Kingdom, as in other countries, a groundwater protection code has been set up for petrol stations and other fuel dispensing facilities that have underground storage tanks. The code applies to any facility which stores hydrocarbons in underground storage tanks.

Fuel oil code to prevent contamination problems with fuel storage tanks
Ontario, California, USA

In Ontario (California) a Gasoline Handling Code has been established. This code includes the fuel oil code which has rules for owners of supply tanks. The rules are as follows:

“The owner of a supply tank or its piping shall:
- Ensure that any leaks are repaired;
- Ensure that any defective equipment or component is repaired or replaced forthwith;
- Take all reasonable precautions to prevent the escape or spillage of fuel oil during all operations including test and repair; and
- Ensure that escaped fuel oil is recovered and contaminated soil is removed forthwith.

Where an underground tank will not be used, or where it has not been used for two (2) years, whichever comes first, the owner of the tank shall:
- Remove any product from the tank and connected piping;
- Remove the tank from the ground and
- remove the piping from the ground or
- purge the piping of combustible vapours and permanently seal the ends of the piping by capping or plugging;
- Where the soil around the tank is contaminated with oil from the tank, remove such contaminated soil; and
- Fill any cavities caused by removal of the tank to grade level with clean fill.”

Offences and penalties are given if one does not follow the rules above.

Any person who:
- contravenes or fails to comply with any provision of the Gasoline Handling Act or the Energy Act;
- knowingly makes a false statement in any document prescribed by the regulations;
- fails to carry out the instructions of an inspector is guilty of an offence and in conviction is liable to a fine of not more than 25,000 US Dollars or to imprisonment for a term of not more than one year, or both, or, if the person is a body corporate, to a fine of not more than 100,000 US Dollars.”

Avoiding groundwater pollution around a petrol station, Iran

Avoiding oil spill contamination from pump sets

Many of the pumps that lift groundwater to the surface are also a source of local contamination. Leakage of oil, petrol or diesel is common. Some of the prevention measures include placing impermeable seals on the soil surface under the machinery, placing the machinery in a reservoir or the construction of a properly floored pump house.

Oil spillage from pump, Yemen

Prevent leaking underground storage tanks
Wisconsin, USA

Underground storage tanks can be a major threat to groundwater quality. A small leak in a tank holding petrol, diesel or fuel oil can cause substantial contamination, particularly as many tanks slowly corrode over time. In Wisconsin over 13,000 leaking underground storage tanks were detected. Older tanks have been removed. Soil under these tanks is then sampled and if necessary remediated. Strict regulations for these have been introduced. Tank systems now must have corrosion protection, leak detection systems, and spill and overfill containment devices (See figure LUST).

Leaking Underground Storage Tank (LUST) due to corrosion

Clearing up old pesticide stocks
Africa

Pesticide stocks have caused immediate threats to the health of the population and posed hazards to groundwater quality (see example in box below). The Africa Stockpiles Programme (ASP) has been set up in order to clear all obsolete pesticide stocks from Africa and set up new prevention measures. Field operations include training staff, creating a national stockpile inventory and safe disposal of the pesticides. Continuation of the project includes promoting safe agricultural management practices, reduced pesticide use, and integrated pest management (IPM). The project will be implemented over 12-15 years. In the first phase, ASP will target their clean-up activities on Ethiopia, Mali, Morocco, Nigeria, South Africa, Tunisia and Tanzania.

AFRICA
STOCKPILES PROGRAMME

Prevention measures regarding road salt

In many cold countries road salt is used as an inexpensive method to de-ice the roads. However, this method has negative environmental consequences. The salt can enter the groundwater through leaching or run-off. In the USA some prevention measures include:

- Using alternative de-icing chemicals, such as Calcium Chloride and Calcium Magnesium Acetate, especially in sensitive areas.
- Road weather information systems are set up to collect data on air and pavement temperature. With the information of these systems, chemicals can be applied before freezing which reduces the amount of chemicals used.
- Efficient spreading, called windrowing, is used in some states. With this technique the salt is applied in narrow strips. This will de-ice a larger part of the road.
- Pre-wetting of de-icing chemicals can result in a lower amount of chemicals needed since it improves infiltration into snow.
- Street sweeping after the snow melts prevents de-icing residue entering the groundwater.

Groundwater contamination due to storage of pesticides without prevention measures
Vikuge State Farm, Tanzania

In 1986 the Vikuge State Farm in Tanzania received 170 tons of pesticide from the Greek government. The State Farm was meant to distribute these pesticides to other farmers. Due to the small size of the containers and the Greek labels on the bottles this caused some complications. The pesticides also contained the insecticide Telodrin, which has been out of production for 20 years due to its high toxicity.

Due to the unsafe storage of the stockpile, the pesticides were exposed to the open air. In 1995 a bushfire caused even more problems. In 1996 the remaining bottles were put in a new storage place.
It turned out that the former storage shed was built on a hill which resulted in high concentrations of pesticides contaminating run-off water. Shallow groundwater was also contaminated. People complained about chemical 'smells' in the water from two shallow wells downstream of the site. Measurements established that these wells contained pesticide residues above WHO recommendations.

Impermeable layer under very porous asphalt
The Netherlands

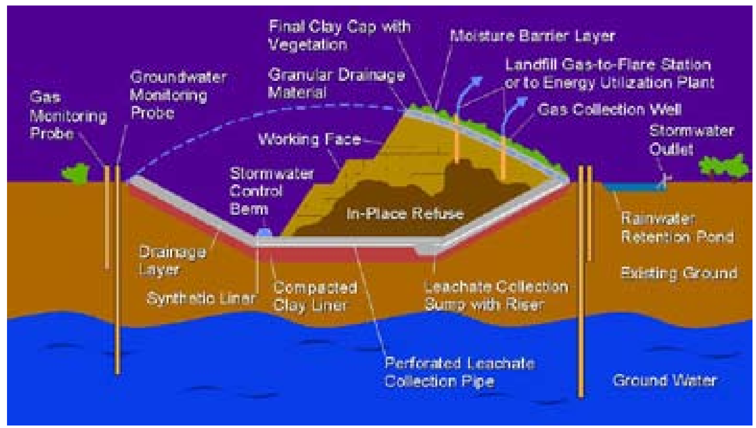
In the Netherlands porous asphalt is used in 60% of the highways. Porous asphalt reduces noise pollution and avoids bad visibility during heavy rainfall. Due to precipitation, harmful substances in run-off water from highways and other roads can cause groundwater pollution. The relative large pores in the asphalt enable precipitation to percolate through the road. Beneath the asphalt coating an impermeable layer is placed. Consequently, precipitation only infiltrates in the area near the road. Oil and other polluting substances stay in the asphalt and are removed periodically.

Liners and leachate collection under landfills
California, USA

In Sonoma County in northern California a Municipal Solid Waste landfill was built 14 m below groundwater level in the East Canyon area. A liner system was constructed. The underdrain layer consists of a geosynthetic clay liner (GCL) with a geomembrane. High permeability gravel was used for the underdrain and the leachate collection layers.

Texas, USA

The Texas Disposal Systems Landfill uses a leachate collection system under landfills to prevent groundwater contamination. The collection system consists of trenches with chipped tyres or gravel, leading to a central collection point. The sides of the landfill are constructed out of compacted clay. This separates the waste from the shallow groundwater.



Cross section of a landfill

5.2 MINIMIZING NON-POINT POLLUTION

Non-point pollution occurs if harmful substances enter groundwater over a large area. Often this is related to agricultural practices that will need to be changed.

Integrated pest management

Integrated pest management (IPM) aims to control pests and crop diseases by using natural and safe methods. Integrated pest management minimizes economic as well as environmental risks. It can help to prevent groundwater contamination from pesticides and herbicides. To prevent pest infestation it is recommended to rotate between different crops, select pest-resistant varieties, and plant pest-free rootstock. These control methods can be very effective and cost-efficient and present little to no risk to people or the environment. Once monitoring, identification, and action thresholds indicate that pest control is required, and preventive methods are no longer effective or available, IPM programmes then evaluate the proper control method both for effectiveness and risk. Effective, less risky pest controls are chosen first, including highly targeted chemicals, such as pheromones to disrupt pest mating, or mechanical control, such as light trapping or weeding. If further monitoring, identifications and action thresholds indicate that less risky controls are not working, then additional pest control methods would be employed, such as targeted spraying of pesticides.

Minimizing conventional pesticide usage

Missouri, USA

In Missouri the back cutworm can cause considerable damage to maize. Cutworms cut seedling stems just above or below the soil surface. Instead of applying preventive pre-plant insecticides, which can contaminate the groundwater, minimal 'rescue treatments' are used. These are based on trap count data and modelling of the larval growth stages. Using this data a decision is made whether or not the maize will be treated. Unnecessary insecticide applications are avoided with this system.

Fencing off water sources from livestock

When livestock defecate in or near the water it can be harmful to nearby water sources. Phosphorus from manure can increase algal growth, ammonia can kill fish, and pathogenic micro-organisms can affect humans. Placing a fence around the water source will prevent grazing livestock from accessing these areas. Special livestock watering options can be used, for example an access ramp or a nose pump. An access ramp provides firm footing and easy access to water while preventing animals (when used with fencing) from trampling the adjacent stream bank. Nose pumps are the lowest cost pumping system available, the power is provided by the animal when it pushes a lever with its nose. The source is protected, since water is pumped through a hose to a holding bowl.

Lining dug wells to reduce return of dirty water in well

In areas with shallow aquifers, dug wells are common. Lining a dug well can contribute to improved water quality. Lining prevents dirty water from the surface from washing into the well. It also reduces dirt delivered by wind or animals. Furthermore the risk of the shaft collapsing and the risk for people or animals falling in the well are prevented by lining. A disadvantage is that once lining is applied, it is more difficult to rehabilitate a dry well.
Different options are possible, for example the entire well can be lined or just around the top. Lining is usually applied to existing wells, and different wells need partial or full lining using different types of material. The table below provides information on suitable lining materials depending on the geology of the source.

Concrete rings for lining open wells in India

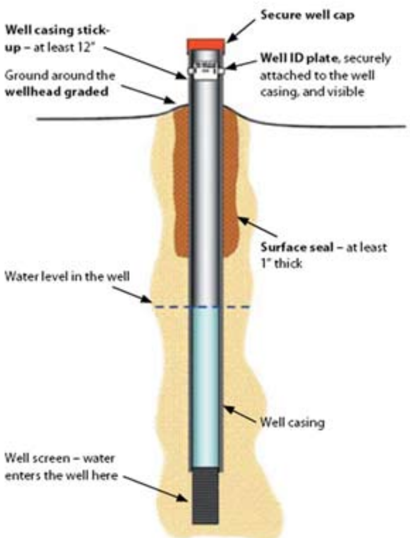
Characteristics of source	Suitable materials	Full or partial lining
Stable sides, diameter of shaft less than 1.3m and greater than 0.9m	All	Partial lining normally sufficient
Well over 1.3m diameter	Brick lining with concrete rings or stone below water	Partial or full
Soft ground / sand	Concrete rings or wood	Full lining
Well less than 1.0m diameter	Widen for brick lining	Partial lining normally sufficient
Well unstable in top selection	All	Partial lining normally sufficient
Well unstable below water level	Concrete rings	Partial lining normally sufficient (may need top lining as well) for shallow wells

Source characteristics and selection of type lining.
Source: Sally Sutton. 2004. Low costs water source improvements.

New standards for water supply wells
British Columbia, Canada

On November 1, 2005 British Columbia (BC) adopted a Groundwater Protection Regulation which established new standards for all water wells in BC. All wells constructed after November 1 2005 have to meet these minimum construction standards. Examples of these standards are (see also figure):

- Applying a surface seal with a thickness of 2.5 cm. Thus, contamination from the surface or shallow subsurface zone will not be able to enter the well.
- A secure well cap will prevent undesirable substances from entering the well
- Well casing should stick up at least 30 cm to protect the well against floods.
- The ground around the wellhead must be graded to prevent surface water from entering the well.
- A well identification plate must be attached to every new well.
- Artesian flows must be controlled or stopped to prevent wasting water.



The diagram shows these new standards (**in bold**). When construction of a well is completed, the well owner should receive and retain the written report on the work from the well driller.

Standards of groundwater protection regulation

Capping abandoned wells
James City County, Virginia, USA

The James City Service Authority (JCSA) has set up the "Let's Be Water Smart" programme. This programme focuses on educating and helping residents to maintain high-quality landscaping and at the same time to use water efficiently. "Cap it" is part of the programme and makes people aware of the importance of capping their abandoned wells. Open wells can cause groundwater pollution for example when pollutants enter the well through storm water run-off. A licenced well driller can cap an old well in a few hours. Capping is inspected by the JCSA to ensure quality and safety standards are met. A limited number of wells are capped free of charge by the JCSA.

Road run-off and Evian's sources
Haute-Savoie, France

In areas with precious groundwater sources such as Evian's in Evian-Les-Bains, road run-off protection measures are implemented to ensure an unpolluted resource. As one of the world's largest bottled water retailer Evian wishes to maintain high groundwater quality. Road run-off in the catchment area is diverted into evaporation ponds where the residue is collected and treated elsewhere.

Community-led total sanitation (CLTS)

Community-Led Total Sanitation (CLTS) is an approach which facilitates a process of empowering local communities to stop open defecation and to build and use latrines without offering external subsidies to purchase hardware such as pans and pipes. Using this approach, local governments, NGOs and international agencies can facilitate community participation to determine what is needed, make decisions, design and execute the work. In this way local innovation and creativity is fostered and supported, and only small-scale investments are needed to initiate learning, and training of community facilitators.

Unprotected wells causing groundwater contamination
Butajira, Ethiopia

Most households near Butajira have wells in their courtyards – thus largely improving livelihoods. These wells are used for small home gardens, watering livestock and all domestic needs.
They are hand-dug and are usually between 5-15 meters deep. Unfortunately most of these wells are unprotected. During pumping and during rain showers, dirt that has accumulated around the wells washes in and contaminates the shallow aquifer. A simple concrete ring or building a small mound around the well would avoid most of these problems.

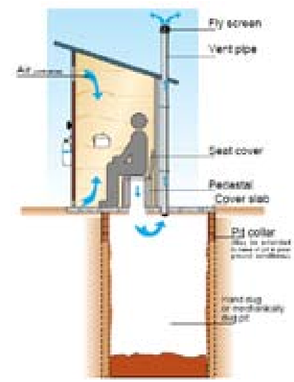
Unprotected well in Butajira, Ethiopia

Pit latrines and groundwater contamination

In many developing countries pit latrines are used for on-site sanitation facilities. Pit latrines are more hygienic than defecating in the open field, yet there are still some issues that should be taken into account regarding health and groundwater contamination when planning a new pit latrine:

- Abstraction of groundwater should be at least 10 m away from the pit latrine
- If there are severe risks to contamination, an artificial sand barrier can act as a filter

Building a Ventilated Improved (VIP) latrine in Ghana



VIP latrine cross section

Alternatives to wood preservatives

Pressure-treated wood is treated with a preservative to protect it from being destroyed by insects, fungus or exposure to moisture. Often the preservative used is chromated copper arsenate (CCA).

CCA is very effective against decay, but can cause groundwater contamination due to leaching. An alternative for CCA is ACQ or Ammoniacal Copper Quaternary, which is a water-based wood preservative that prevents decay from fungi and insects (i.e., it is a fungicide and insecticide). ACQ does not contain arsenic which can lead to health problems.

Prevent pollution from septic tanks

Septic tanks are connected to the sewerage system of a house. Laundry, sink and toilet wastewater are collected in the septic tank. Decomposing bacteria in the tank break down the organic material and reduce the quantity of nutrients and pathogens. The liquid effluents flow from the tank into a septic field or a sewer system. The vegetation and the soil in the septic field filter the effluent. The sludge and scum layer remaining in the tank should be removed every two to three years. Leaking septic tanks can become a major source of groundwater contamination.
To avoid contamination from septic tanks it is best to plant grass on the septic field rather than trees or bushes. Firstly, grass has a better filtering effect and secondly trees may penetrate the septic system with their roots. Biomats can be used to slow down the movement of effluent to one percent of the normal downward flow. A biomat is a biological layer formed by micro-organisms that anchor themselves to the soilrock interface. This results in the soil remaining in an unsaturated condition for a longer period than usual, which aids in preventing transmission of pathogens.

5.3 PROTECTING GROUNDWATER RESOURCE AREAS

Special protection measures may be taken to protect groundwater from pollution, so as to safeguard the long-term availability of good-quality drinking water. Such measures include zoning of certain land uses or practices, complemented by special activities and regulations. In the USA for instance all states have Wellhead Protection Programs approved by the Environmental Protection Agency.

Road sign to indicate drinking water protection area, USA

Using road signs to mark groundwater protection areas
Global

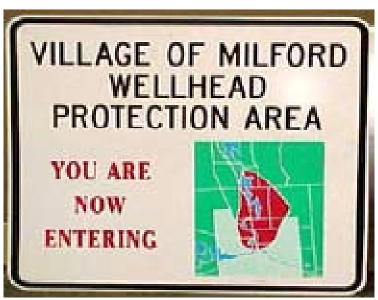
One way to make people aware that they are in a protected area is to place signs along the road. Preferably short descriptions of do's and don'ts should be part of the road sign.

Road sign to indicate groundwater protection area, The Netherlands

Road sign to indicate groundwater extraction area, France

Using different zones for wellhead protection
Ontario, Canada

In Ontario three zones are defined relating to wellhead protection. The zones are based on the direction and rate of the groundwater flow to the well. With computer models, the time for groundwater to travel a certain distance can be mapped. Three zones are distinguished: *Zone 1* is the most sensitive area around the wellhead. In this zone groundwater can reach the well in less than two years. It is important to manage land-use activities in this area since not all contaminants break down during this period. *Zone 2* is located further from the well. It takes 10 years for groundwater to reach the well. The risk in this zone is from hazardous chemicals. In *Zone 3* it takes 10-25 years for groundwater to reach the well. In this zone the more persistent and hazardous contaminants are controlled.



Sign on wellhead protection area, USA

Special measures in groundwater protection areas
New Hampshire, USA

By ordinance most states in the USA have established Groundwater Protection Overlay Districts. Within such districts, special measures are in force and are often complemented with public education. In New Hampshire, the ordinance prohibits the following practices within the Aquifer Protection Zone:

- On-site disposal, bulk storage, processing or recycling of toxic or hazardous materials or wastes.
- Underground storage tanks except as regulated by the New Hampshire Water Supply and Pollution Control Commission. Storage tanks, if contained within basements, are permitted.
- Dumping of snow carried from off-site.
- Automotive uses including: car washes, service and repair shops, junk and salvage yards.
- Laundry and dry-cleaning establishments.
- Industrial uses which discharge contact type wastes on site.

Violating any of these provisions results in a fine of around US$ 10 for each day that the ordinance is breached.

Defining groundwater protection zones
The Netherlands

In the Netherlands groundwater protection zones are defined according to the following principles:

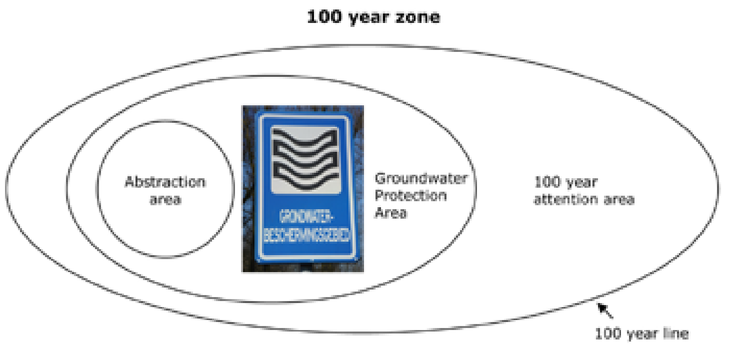
- Water abstraction areas are commonly owned by the water supply companies and can vary from 0.25-7 hectares. The depth of abstraction varies according to the quality and flow of the groundwater.
- Around some of the abstraction areas a groundwater protection zone is delineated, recognisable from the road

signs. On average a protection area is 1-3 km wide, in these areas the provincial governments are extra vigilant to prevent any harmful activities.

- A 100 year zone is also identified according to the hydro-geological principles that within this area groundwater is estimated to reach the abstraction point between 25 and 100 years. In this area it is prohibited to drill wells to certain depths since protective clay layers may be perforated.

Phasing out injection wells
USA

The EPA estimated that there are approximately 1 million injection wells in the USA that were constructed in the past to dispose of



harmful substances. These consist of motor vehicle waste disposal wells, industrial waste disposal wells and large-capacity cesspools. They present one of the greatest threats to underground sources of drinking water. The 1996 Amendments to the Safe Drinking Water Act require states to establish Source Water Assessment Programs, in line with their particular needs and conditions. Within source water protection areas, cesspools must be phased out within a period of five years. Motor Vehicle Waste Disposal Wells are either to be banned or like industrial wells are only allowed to discharge water with the same quality as the aquifer's water.

Protection measures to avoid pesticide contamination in wells
North Carolina, USA

Envirosense, North Carolina produced a fact sheet on how to prevent well contamination from pesticides. A few recommendations are made for well owners regarding pesticide use including:

- Do not mix or apply chemicals near the well
- Use a long hose at least 100 ft away from the well when loading and mixing pesticides
- Avoid backflow by keeping the end of the hose above the fluid level in the tank
- Locate the well on the highest suitable ground to prevent contamination from run-off

Local groundwater study leads to groundwater protection measures
Ontario, Canada

A local groundwater management study in Larder Lake, Ontario was carried out. Part of this study was mapping the groundwater system, constructing groundwater flow models, identifying potential contaminant sources, preparing an emergency plan and drilling nine boreholes to collect data.
Based on this research a few measurements to protect the groundwater were taken in Larder Lake:

- Removal of the snow dumping site
- Upgrading of salt storage facility
- Problematic septic tanks connected to the sewage system

Prevent the removal of clay layers
Tete City, Mozambique

A groundwater protection committee was set up for Nhartande Valley. The basic aim of the committee was to prevent further removal of clay from the river bed for brick making. The removal of this clay layer from a dried up tributary of the Zambezi River was resulting in accelerated pollution of the urban groundwater sources from septic tanks and other uses on the slopes of the valley, as the aquifer was no longer sealed off. The Groundwater Protection Committee was initiated by the Rural Water Department (DNA), but struggled to become effective because of the strong influence of other stakeholders. The urban water company was not actively engaged and more occupied with service delivery rather than source protection.

5.4 USE OF SAFE SOURCES

A fourth strategy is to ensure that safe groundwater sources are used, either by carefully selecting groundwater sources or by water treatment. The most important source of contamination is bacteriological. Arsenic and fluoride are two important chemical contaminations.

Use bleaching powder to clean wells
North Bengal, India

At the end of the rainy season, water quality in many rural dug wells deteriorates because of excessive growth of vegetation. Dead ferns and other vegetation fall into the water and rot. To improve well water quality, farmers pump their wells dry and add bleaching powder to neutralize any remaining organic material.

Ceramic-Silver Filter (CSF)

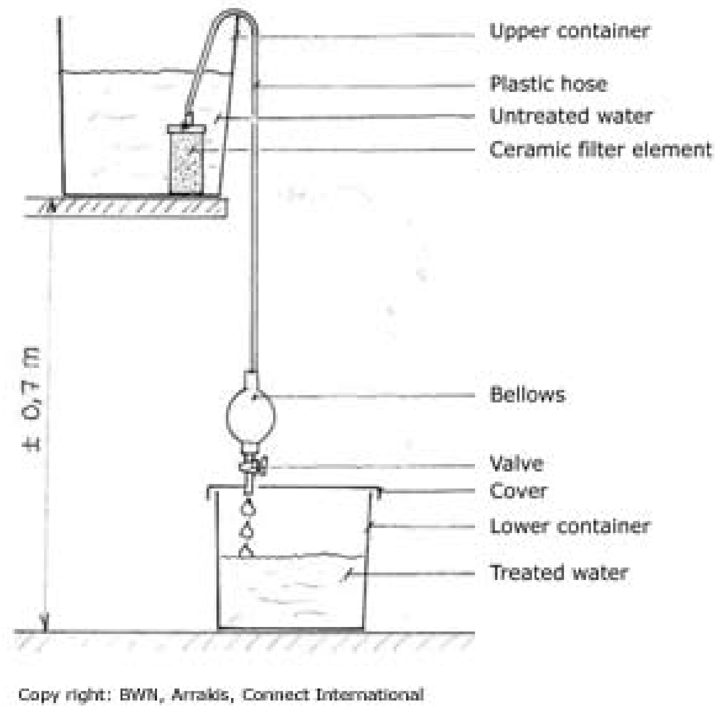
The ceramic-silver filter is an alternative to the conventional ceramic candle filters. The filtering element from the CSF is ceramic treated with colloidal silver. This filter eliminates 98-100% of bacteria causing waterborne diseases. Filling up this filter two times a day will give 15-20 l of clean water. The CSF is used in UNICEF and Red Cross projects. It is a cheap method; one silver treatment will cost 0.15 US$. To maintain the CSF it is cleaned with a brush and the element is changed every two years.

Sand filters

Sand filters are very effective in removing common pollutants from storm water run-off. Three main types of sand filters are distinguished: rapid sand filters, slow sand filters, and up-flow sand filters.
Rapid sand filters are commonly used in municipal water treatment plants. To remove particles and impurities relatively coarse sand is used. The water flows through the filter medium under gravity or under pressure. Rapid sand filtration is often used in combination with other purification methods since the water flows quickly through the filter bed with a filtration rate of up to 21 m per hour. Slow sand filters have a filtration rate of up to 0.4 m per hour. The filtration bed in slow sand filters contains very fine sand and can therefore remove particles that are smaller compared to rapid sand filters.
For up-flow sand filters, vessels are filled with layers of sand, gravel and pipework to force the water to flow upwards through a filter. The vessels can be placed in a container of clay, metal or plastic. Sand filters become clogged with floc after a period in use. They can be backwashed or pressure washed to remove the floc.

Siphon filters

The siphon filter is a new low-cost water household level filter option. It eliminates turbidity and bacteria. It consists of a high quality ceramic filter element, a siphon hose, a suction bulb and a valve. A vacuum is created which makes the water flow through the filter. Because of this the siphon filter procures more clean water than other low-cost filters. When clogged it can be backwashed. Tests are being carried out in Africa and India and this filter will be available on the market soon.



Siphon filter (schematic drawing)

Common water treatment methods

Besides individual water treatment systems many methods exist for domestic use:

- ***Boiling***
  If the water is boiled long enough (for at least three minutes) pathogens will be killed.
- ***Distillation***
  This can be seen as the reverse of boiling. Pure steam from boiling water condenses back into liquid water.
- ***Reverse osmosis***
  This method is based on differences in water pressure. Treated water and untreated water are separated by a membrane. The water pressure forces the water molecules through the membrane leaving behind contaminants.
- ***Water filtration***
  Contaminants stay behind in the filter medium.
- ***Ultra violet light method***
  Exposing water to UV light will remove some organic contaminants.
- ***Water softeners and deionizers***
  Based on ion exchange processes where hardness minerals attach themselves to resin beads while sodium on this resin bead is released simultaneously into the water.
- ***KDF-filters***
  Based on electrochemical oxidation and removes chlorine, kills algae, reduces hardness, controls bacterial growth and removes inorganic compounds.
- ***Ozonation***
  Ozone acts as oxidizer and will oxidize all bacteria, organic material and viruses
- ***Activated alumina***
  Activated alumina absorbs contaminants and can reduce levels of fluoride, arsenic and selenium.
- ***Altered water***
  This is water which is treated to enhance health effects. A large variety of methods are known; pi mag, oxygenation, magnetic treatment, etc.

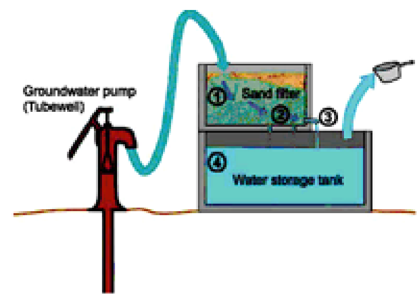
Source: Drinking Water Resources on www.cyber-nook.com

Colour coding of safe wells
West Bengal, India

Arsenic contamination has turned into an enormous problem in Bangladesh and South West Bengal in India, affecting upward of 100 million people. The causes are unknown, but the most likely explanation is that with the lowering of groundwater tables, arsenic was released from geological formations. The arsenic concentration varies from well to well. To distinguish safe wells from unsafe wells different colours are used.

Household sand filters to remove arsenic
Red River Delta, Vietnam

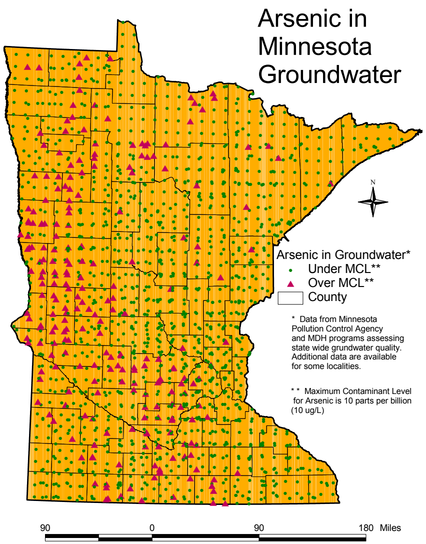
In the Red River Delta in Vietnam sand filters are used to remove arsenic from groundwater. The filter consists of an upper tank filled with locally collected sand and a water storage tank. These tanks are made of bricks or concrete. The upper tank is connected to contaminated groundwater and has an outlet to the storage tank. In the upper tank a sieve is placed to prevent the sand from flushing out of the filter. A sand filter reverses the process of arsenic release in groundwater; initially dissolved iron will precipitate on the sand and form the absorbent for arsenic.
After the sand filter has been used the filter sand needs replacing, once every 1-2 months and as arsenic does not re-desorb it can be disposed of on roads or riverbeds, but not irrigated fields where anoxic conditions can occur.



Household sand filter

Water treatment systems

Minnesota, USA



In Minnesota, arsenic occurs naturally in about half the wells. To purify the water, water treatment systems can be installed. At the Minnesota Department of Health, treatment systems from independent certifiers such as the National Sanitation Foundation (NSF) are recommended. First, the quality of the well water needs to be tested, and treatment depends on these results.

Removing iron bacteria in water wells

Iron bacteria which grow on well screens, pumps or within the surrounding aquifer, can significantly reduce the efficiency of a well in a short period of time. Plant foliage watered by overhead irrigation systems shows a blue sheen and dark spots if the well water used contains bacteria. Successful removal of iron bacteria from wells can be done in two steps; first the bacterial mass and associated insoluble precipitants need to be broken up and removed, second the well screen, pump and adjacent aquifer need to be sterilized to reduce the residual bacteria population.

Arsenic

Arsenic is an element which occurs in the ground naturally, but arsenic has also been used in many activities throughout human history such as industrial processing, livestock farming and mining. Arsenic can be found in a harmless organic form or in a toxic inorganic form. The latter can be absorbed and accumulates in the body over time causing long-term harm. It is hard to detect arsenic because it is tasteless, odourless and colourless. Arsenic can cause damage to the nervous system. Examples of diseases caused by arsenic are: cancer of the lung, skin, prostate, kidney and liver, diabetes mellitus and hypertension. The WHO's guideline value for arsenic in drinking water is 0.05mg/l (given a provisional guideline value of 0.01mg/l in 1993).

Arsenic treatment systems
A common and innovative arsenic filter is the Sono Filter. The Sono filter uses composite iron matrix (CIM) as the active arsenic removal component. It was proven that CIM is the only system where arsenic removal efficiency increases with the increased volume of groundwater filtered. These filters can produce 120 l (at 30 l/hour) of clean water for drinking and cooking. For about US $35 they can last at least five years without a toxic waste disposal hazard. New models are developed for community-scale use with a flow rate exceeding 100 l per hour.

Another arsenic filter is the sand filter, developed in Vietnam. The arsenic removal is based on the principle that dissolved iron precipitates, forms insoluble iron(hydr)oxide, which coats the surface of the sand particles. The oxidation process releases oxidants which can oxidize arsenic AsIII to arsenic AsIV/AsV which adsorbs to the coated sand particles. A precondition for an efficient sand filtration process is that there are considerable iron levels (optimally > 12mg/l) in the water and low phosphate levels (as phosphate competes with arsenic for adsorption sites on the iron(hydr)oxides).

Tibiri's tragedy
Tibiri, Niger

Hundreds of children aged 15 months to 14 years developed skeletal fluorosis, caused by the consumption of water from Tibiri's domestic water supply system. From 1983 onward, the Société Nigérienne des Eaux (SNE) supplied water from deep wells, unaware of the presence of fluoride in the groundwater. Fluoride levels had not been investigated during the construction of the wells and were not tested for in the standard drinking water tests. Between 4.8-6.6 mg per litre were found in SNE water supply facilities – far above the 1.5 mg recommended by the World Health Organization. The consequences were disastrous with children disabled for the rest of their lives. An alternative source of water was used from the neighbouring town of Maradi, where fluoride levels were acceptable.

Using oxidizers and acidifiers are two of the most common methods of breaking down the mass of bacteria. The pump and pump column are removed and cleaned and the wells are physically agitated when using the oxidizers or acidifiers. Finally the wells are purged until the water is of the same composition as before remediation.

Recharging aquifers with rainwater in fluoride areas
Balisana, India

Balisana, a village in the Gujarat district in India, suffers from severe fluoride levels in the groundwater. As an alternative source for drinking water a combination of groundwater recharge and shallow wells was developed. A bund 12 km long was reconstructed to retain water from rainfall. Through a three metre-wide canal, the rainwater was led into a tank. Next to the tank a recharge well was made. The recharge well is supplied from the tank through a horizontal pipe.

Source contamination settlement
California, USA

'She brought a small town to its feet and a huge company to its knees' The Oscar-winning movie 'Erin Brockovich' is based on a real-life story. In the movie, Julia Roberts plays a research assistant who, in 1992, helped attorney Ed Masry to win a US$ 333 million settlement against the Pacific Gas & Electric Company (PG&E), which was the largest settlement ever awarded in an environmental dispute. Masry and Ms Brockovich represent 650 people who blamed PG&E for contamination of their water supply originating from a power plant. The groundwater being the water source for the small desert community of Hinkley, California was contaminated with the highly toxic Chromium VI (Chromtrioxide) which had caused cancer and other illnesses among the population of the town.
Erin Brockovich gathered evidence (which had been carefully suppressed), gained the confidence of the residents of the small community and won the trial. Although the story is extraordinary and worthy of Hollywood treatment, it is an example of promoting transparency and justice through single-minded action. The movie was based on real life litigation on groundwater pollution. Erin Brockovich continues the struggle and has recently been involved in exposing chromium pollution in Oinefyto in Greece.

Fluoride

Fluoride is a common constituent of groundwater. Natural sources are connected to various types of rocks and to volcanic activity. Agricultural (use of phosphatic fertilizers) and industrial activities (clays used in ceramic industries or burning of coals) also contribute to high fluoride concentrations in groundwater. Fluoride has a significant mitigating effect against dental cavities if the concentration is approximately 1 mg/l. However, continuous consumption of higher concentrations can cause dental fluorosis and in extreme cases even skeletal fluorosis. High fluoride concentrations are especially critical in developing countries, largely because of lack of suitable infrastructure for treatment.

Fluoride treatment systems
When fluoride levels are high, the preferred strategy is to identify a safe source free of fluoride, even if this means conveying water over large distances. If this is not possible, water should be defluoridated. Several methods can be suggested, all with peculiar demands in terms of management (supply of chemicals, removal of sludge, maintenance). The defluoridation methods are divided into three basic types depending upon the mode of action:

1. Based on chemical reaction with fluoride
The best known technique is the Nalgonda, named after the village in India where the method was pioneered. The Nalgonda technique uses the flocculation principle. When aluminium sulphate and lime are added to fluoride-rich water the chemicals react, flocculate and are easy to remove. Main advantages of this technique is that only readily available chemicals used in conventional municipal water treatment are required, it is highly efficient in removing fluoride, needs minimal mechanical and electrical equipment, and no energy except muscle power for domestic installations.

2. Based on the adsorption process
Fluoride in water accumulates on the surface of the solid or liquid adsorbents. Adsorbents which can be used are: bone charcoal or processed bone, tricalcium phosphate, activated carbons, activated magnesia, activated alumina, tamarind gel, serpentine and more readily available plant materials such as bark of the horseradish tree (*Moringa olifera*) and Indian gooseberry tree (*Emblica officinalis*), and the roots of the vetiver or khas-khas (*Vetiveria zizanoides*).
In this process the water containing contaminants glows through a canister with, for example, activated alumina. The activated alumina absorbs the contaminant.

3. Based on the ion-exchange process
Anion exchange resins are found to remove fluorides either by the hydroxyl cycle or chloride cycle along with other anions. Cation exchange resins impregnated with alum solution have been found to act as defluoridating agents.

H2S test as indicator for faecal contamination
The H2S test is low in cost and does not require sophisticated equipment to manufacture or to carry out.
The test uses a medium with thiosulphate as a sulphur source and ferric ammonium as an indicator to which only certain bacteria will produce hydrogen sulphide which reacts with the thiosuplhate and forms a black precipitate.
To carry out the test the paper H_2S strip must be impregnated with boiled water and a common liquid detergent. The paper must be dried in a low-temperature oven. The dried paper strip is placed in a clear small plastic or glass bottle or tube. A water sample is collected in the container containing the reagents and stored in the dark at room temperature for about three days. If the sample contains hydrogen sulphide-producing organisms, the pad and water turn black.

5.5 REMEDIATION

Over the years a large number of groundwater bodies have been contaminated, often with highly toxic effluents. Many such water bodies are located close to urban centres and the only resort to restoring this vital asset is groundwater remediation.

***In-situ* mercury removal**
USA

Adventus America has developed a family of bioremediation products used for *in-situ* treatment of groundwater called EHC-M. The products contain a carbon component that encourages precipitation and adsorption of mercury (or other dissolved materials like arsenic) and limits their movement, facilitating their removal. According to a recent study, EHC-M achieved a removal of total mercury greater than 99%.

Addressing arsenic contamination from tin mines
Nakhon Si Thammarat, Thailand

Arsenic contamination is common near many gold and base-metal-producing mines. In Thailand, health problems related to arsenic-contaminated water supplies were first highlighted in 1987, following the diagnosis of a case of arsenical skin cancer in Ron Phibun District, Nakhon Si Thammarat Province. Investigations established that shallow wells and sites around Ron Pibun village had concentrations exceeding WHO's standards (in some cases 50-100 times higher). The sources of the arsenic contamination in this case were the old tin mines and primary and secondary tin ore deposits. Contamination countermeasures involved: removing contaminated soil, monitoring and treating contaminated water, educating inhabitants on proper land use and devising a management policy for future use of the site.

Groundwater remediation techniques

The Ground-Water Remediation Technologies Analysis Centre describes numerous *in-situ* remediation technologies divided into three groups: Physical/chemical treatment, biological treatment and electrokinetics.

Physical/chemical treatment:

- *Air sparging* - With this technique gas, such as oxygen, is injected into the well in the saturated zone. Dissolved contaminants in groundwater are volatized and move upward where they can be removed in the unsaturated zone.
- *Blast-enhanced fracturing* - Where fractured bedrock occurs, this technique can be applied to improve the rate and predictability of the recovery of contaminated groundwater. Through explosions highly fractured areas can be created.
- *Directional wells* (also named horizontal wells) - These are directly drilled wells on slopes to reach contaminants that are not accessible by direct vertical drilling. After drilling the directional well, *in-situ* remediation techniques can be applied more easily.
- *Groundwater recirculation wells* - This technique integrates principles of groundwater recirculation with air stripping of volatile organic compounds. Injection of air creates an airlift pumping system which causes groundwater with air bubbles to rise. The water exits beneath a divider and vapours are collected by a vacuum pump. Groundwater re-enters the contaminated zone into the stripping well again. This process will be repeated until the water is completely remediated.
- *Hydraulic and pneumatic fracturing* - Soil permeability is increased by creating fractures, thereby accelerating contaminant removal. With hydraulic fracturing, fractures are made by injection of high pressure water, sand and thick gel into the bottom of a borehole. For pneumatic fracturing highly pressurized air is used.
- In-situ *flushing* – Chemicals like surfactants and cosolvents help to dissolve non-aqueous phase liquids (NAPLs). These are liquids that do not dissolve in water such as heating oils. With *in-situ* flushing a mixture of water and surfactants or cosolvents is pumped down a well into the polluted zone where it can dissolve the NAPLs or move the NAPLs towards the well.
- In-situ *stabilization/solidification* – This is a process where chemical reactions are induced between stabilizing agents and contaminants to reduce their mobility (stabilization) or contaminants are bound within a stabilized mass (solidification).
- *Permeable reactive barriers* – This barrier forms a treatment zone where contaminants in groundwater will be immobilized when the groundwater reacts with reactive materials within the zone. At strategic locations treatment walls are installed. Through natural gradients, contaminants are transported through these barriers. The barriers may contain reactants which enhance the breakdown of contaminants into harmless by-products.
- *Thermal enhancements* – By using steam, temperature-dependent properties of contaminants are mobilized. Vaporized contaminants rise to the unsaturated zone where they are removed and treated.

Biological treatment:

- *Bioslurping* – Uses vacuum-enhanced pumping and bioventing (providing oxygen to stimulate naturally occurring soil micro-organisms to degrade compounds in the soil) to promote biodegradation.
- *Monitored natural attenuation* – This technique relies on a variety of physical, chemical or biological processes that leads to a reduction of contaminants in groundwater without the interference of humans. Ongoing monitoring is required to determine whether contaminant concentrations are decreasing.
- *Phytoremediation* – By using plants the contaminants in groundwater are removed. Numerous techniques can be used, for example:
    - Rhizofiltration: filtering groundwater by plant roots.
    - Phytoextraction: uptake of contaminants and storage into the plant
    - Phytotransformation: the plant will uptake substances and degrade them by metabolism
    - Phytostimulation: microbial activity will be enhanced around plant roots to stimulate the degradation of the contaminants
    - Phytostabilization: the movement of contaminants will be reduced

Electrokinetics

Electrokinetics – This process involves application of electrode pairs in the ground on each side of the contaminated area. This causes electro-osmosis (movement of groundwater from the anode to the cathode of an electrolytic cell) and electro-migration (transport of ions to the electrode of opposite charge). This process separates and extracts heavy metals and other contaminants from soils or sediments.

Mining Waste Directive to improve management of waste disposal
Europe

Apart from the inherent risks of mining, mines can also contribute to groundwater contamination. The extent of this depends partly on the mine composition and the minerals which are being extracted. A mine can continue to contaminate the groundwater even after it has been abandoned. In 2003 the European Commission proposed the *directive on the management of waste from the extractive industries*, also known as the *mining waste directive* (MWD). This directive focused mainly on improving the management of future mine waste disposal activities, even though overall Europe has experienced a net decline in mining, and it is unlikely that many new mining ventures will become operative in the future. The MWD falls short in focusing on a possibly more severe problem, namely the abandoned mining sites which pose a serious pollution problem, and for which no legally responsible party tends to exist.

Between 2001 and 2004 the European Commission Fifth Framework Programme provided financial support for the Environmental Regulation of Mine Waters in the European Union (ERMITE) research and development project. In November 2003 the following strategic 'economical' steps for mine water management programmes were formulated in the ERMITE Policy Briefs (No 2.3):

a) Identify possible mine water related water quality problems and other possible sources for the same type of problems within relevant coupled groundwater and surface water catchments of managed water environments;
b) Investigate all possible means of improving water quality in affected water environments and calculate associated improvement costs;
c) Choose the preferred economic decision rule for actual allocation of water quality improvement measures within each catchment.

Remediation of groundwater under landfill
New Jersey, USA

The Lone Pine landfill in New Jersey was operated between 1959 and 1979 and over 17,000 drums of chemical waste, municipal refuse and liquid chemical waste were disposed of at the site. The Environmental Protection Agency (EPA) signed a Record of Decision (ROD) in 1984 to clean up the contaminated groundwater and landfill leachate. It decided to carry out a remedial investigation and feasibility research to determine how to minimize the impact of groundwater contamination. Based upon this research the following actions were taken:

- A 2800 ft long interceptor drain was installed to prevent contaminated groundwater from entering the Manasquan River
- Extraction and injection wells were drilled
- Contaminated groundwater was treated on-site
- To restrict groundwater usage in the area institutional controls were created
- A monitoring programme was set up

Maps guide remediation interventions

Rotterdam, The Netherlands

In the Netherlands, the Harbour Company Rotterdam and TNO (an independent knowledge company) are using the WELCOME-strategy to remediate large-scale soil and groundwater contaminated areas. The WELCOME-strategy aims for the most cost-effective control of groundwater quality in the area of Rotterdam.
Maps clearly indicating the sources and types of pollution and plumes and their impact on surface, groundwater and drinking water protection areas, enable prioritization of remediation measures. With the help of soil and groundwater models the risk of pollutant dispersal is assessed and the most appropriate (*in-situ*) measures are identified. Considerations are made and accordingly pollution can be tackled either in the aquifer, the dispersal pathway or at the pollutant's source itself.

Bioremediation with micro-organisms

Saxony and Thuringia, Germany

The legacy of the intensive uranium mining and milling which occurred from 1952 to 1989, in the Saxony and Thuringia area of Germany, was significant pollution by uranium and other toxic metals. Uranium, a persistent radionuclide in groundwater is a significant human health hazard. However, over time the uranium mining waste piles have become a breeding ground for bacteria that have developed special strategies to survive in these extreme environments. Research is ongoing into effectively deploying these micro-organisms to neutralize uranium. The micro-organisms can mobilize radionuclides, which provides a route for removal from solid matrices such as soils, sediments, dumps and industrial

Hanford's 1.7 trillion litres of liquid waste - California, USA

Fifty years of nuclear weapons production resulted in approximately 1.7 trillion litres of liquid waste being released into the ground at the Hanford waste site. Some of the associated contaminants have reached the groundwater. Hazardous chemical contaminants include carbon tetrachloride, chromium and nitrates. Radioactive contaminants include iodine-129, strontium-90, technetium-99, tritium and uranium. Although the Hanford site is not a source for domestic water supply, an area of 207 km^2 has groundwater contaminant levels greater than drinking water standards. However, a remediation programme is underway. Under the auspices of the U.S. Department of Energy, Fluoride Hanford aims to clean up groundwater contaminants, avoid future groundwater contamination, and prevent groundwater contaminants from migrating to the Columbia River. Accelerated clean-up is designed to return groundwater to beneficial use, where possible, or at least prevent further degradation.

Groundwater Remediation Project Mission:
To protect the Columbia River from contaminated groundwater resulting from past, present, and future operations at the Hanford Site and to protect and restore groundwater.

1. Remediate high-risk waste sites – Clean up waste sites that pose the highest risk to groundwater (completed in 2011)

2. Shrink the contaminated area – Reduce the contaminated surface area so it can be released for other purposes (completed in 2009)

3. Reduce recharge – Reduce the transport of contaminants to groundwater from natural and artificial recharge (completed in 2012)

4. Remediate groundwater – Implement final remedial actions at pump-and-treat sites (completed in 2006)

5. Monitor groundwater – Determine the groundwater monitoring needs for long-term stewardship of the Central Plateau and evaluate new technologies that may be more effective

wastes. Alternatively, immobilization processes can be applied for the removal of metals from the groundwater itself.

Prevent contamination by drainage systems
Montana, USA

More than 100 years of pollution needed to be cleaned up in an abandoned area known as the Old Works in Montana, USA. The Atlantic Richfield Company (ARCO) had to choose between removing tons of waste made by smelting and mining activities or remediating the soil.

The soil contained arsenic which could have seeped into and contaminated the groundwater. After carrying out some research and consulting the community, ARCO decided to turn the area into a golf course. Numerous remediation activities took place. Regarding groundwater, the most important activity was to set up a complex drainage system. This system transports water to contaminated areas which are covered by lime rock and capped by clay soil and grassed topsoil. The drainage system captures the excess irrigation and storm water and leads this to irrigation ponds which are covered by protective material.

6| ESTABLISHING GROUNDWATER MANAGEMENT ORGANIZATIONS

Farmers meeting in Tihama, Yemen

In most areas, intensive use of groundwater was uncommon prior to the arrival of pumpsets. Almost everywhere the development of management systems and organizations has not kept pace with the exploitation of groundwater. Gradually management systems come in place – through informal rules and individual behaviour, through local groundwater management organizations and through government regulation and law.

6.1 INFORMAL SYSTEMS OF GROUNDWATER MANAGEMENT

Social norms to ban development of dug wells and tube wells
Panjgur, Pakistan

In Panjgur, karezes are used for irrigating the land. Karezes are horizontal wells that often stretch over a long distance. The karezes pick up the sub-surface flow of the Rakhsan River and then transport the water at a gentle slope before surfacing near the agricultural area.

In Panjgur a rule came into existence which bans the development of dug wells and tube wells in the kareze area. This rule was developed after the kareze owners witnessed the rapid decline of the groundwater table in a nearby area, following the development of electric dug wells. The ban concerned the development of individual dug wells. New collectively owned karezes could still be developed. The ban was informal and not supported by a special organization. Essentially this ban could be enforced by anyone; individuals could stop individuals from digging a well, if necessary by force.

Harim groundwater rule
Middle East

The oldest groundwater rule is described in Islamic law, the so-called *harim* or 'border' rule. The *harim* describes the distances between wells and springs. The rule is still in force in some parts of the Middle East and West Asia and is usually interpreted as a minimum distance between two water points of 350 or 500 m, depending on the local geology.

Run-off rights
Yemen

In Yemen there are a few areas where groundwater rules have been defined; rights to mountain run-off are quite common.

Run-off zones for the hamlets of Al Abin, Yemen

Well recharge movement
Saurashtra Gujarat, India

In 1978 a charismatic leader called Pandurang Shastri Athawale spoke at the inauguration of a common property forest and said: 'If you quench the thirst of Mother Earth, she will quench yours...' After three years of drought from 1985 to 1987 farmers became aware of what was meant by this. Pandurang Athawale asked followers to adopt worldwide used techniques for harvesting and conserving rainwater. Eventually a successful recharge movement was catalyzed with numerous new water harvesting techniques implemented. Following Pandurang saying `the rain on your roof, stays in your home; the rain on your field, stays in your field; rain on your village, stays in your village' the villagers tried out alternative methods of capturing rainwater and using it for recharging wells. Unlike what people did ages before, they started collecting as much rainfall as they could on their fields and in the village and channelled it to a recharge source. This resulted in a wave of individual investments in recharge measures such as small diversion bunds and recharge wells. As this was done intensively in the villages concerned, the impact on the water table became noticeable. These successes then triggered many followings and water recharge became a 'movement'. In several areas, water users imposed restrictions on the development of new wells, after having invested so much in the groundwater recharge systems.

Using traditional negotiation systems
Silmiougou, Burkina Faso

In Silmiougou in Burkina Faso the traditional 'parley' was used to settle a conflict between the villagers and the alien Mossi people. The 'Parley' is a discussion amongst the heads of the families and clans. In this type of discussion all local affairs are discussed and solutions are found that everyone accepts. A conflict was avoided and an arrangement was agreed whereby everyone could make use of the wells.

Promoting local regulation though participatory groundwater monitoring
Andhra Pradesh, India

The Andhra Pradesh Farmer Managed Groundwater Systems Project (APFAMGS) has successfully promoted behavioural change leading to voluntary self-regulation in groundwater use. Using an approach of continuous engagement, by equipping groundwater users with the necessary data, skills and knowledge to manage groundwater, the stressed local resources have been given a rebirth. The main pillars of the project are:

- Establishing institutions such as groundwater management committees at the village level (emergence of local governance)
- Gender mainstreaming through recognising and taking into account the attitudes, roles and responsibilities of men and women
- Enhancing farmers' knowledge in areas such as water resource availability and management, data collection and analysis
- Participatory Hydrological Modelling, transforming individual groundwater users into water resource literates (rainfall recharge relationship, pumping capacity of bore wells, crop water requirements)
- Crop water budgeting, collectively making crop plans (abstaining from paddy, crop diversification)
- Optimization of flood flows through artificial groundwater

recharge, trapping basin flood flows in tanks or ponds
- Data base and geographical information systems, enhanced collection and information access on individual and shared resources

In many of the areas farmers have formed groundwater committees and have adopted measures such as crop change, improved tillage methods (pre-rainy season ploughing for instance), promotion of water harvesting, use of compost and restrictions on well development.

Identifying measures in a participatory process
Amman Zarqin Basin, Jordan

In the Amman Zarqin Basin in Jordan, the farmers developed common measures on groundwater management through a participatory process. The process consisted of stakeholder discussions, field interviews, presentations of water overview, farmers' questions, group meetings and workshops. The most important conclusions reached by the farmers were:
- reducing irrigation water consumption without income losses;
- gaining more information on conservation methods;
- metering is no option since the farmers do not accept charging.

These conclusions lead to several measures, for example a ban on unlicensed drilling and the exploration of local water harvesting.

Stakeholder discussion on groundwater management in Amman-Zarqin Basin, Jordan

Multi-stakeholder process leading to a water allocation plan
Namibia

In Namibia's karst-dominated topography, stakeholders have come together in a voluntary and advisory body: the Karst Water Management Body (KWMB). The KWMB has successfully involved all relevant stakeholders and addressed the emerging water scarcity issues. Its main purpose is to achieve maximum security in the supply of water, with the objective of avoiding over-abstraction and depletion of the water resources. The KWMB consists of an equal number of representatives from the regional and local government, non-governmental institutions, farmers, line ministries and the mining sector. A water allocation plan which outlined how the available water resources could be divided among the various user groups was set up, using the local knowledge of the KWMB. Allocation priorities were set as: water for local domestic and livestock consumption, local industrial supply, abstraction of water for primary and secondary consumption, and local irrigation.

6.2 GROUNDWATER USER ASSOCIATIONS

Omar Enb al Khattab Water User Association bans new wells
East Delta, Egypt

In 1993 one of the landowners in Salheia organized a get-together of 400 landowners in the area. The landowners decided to use a limited number of wells and they developed a common network of pipelines. This agreement resulted in a Water User Association called Omar Enb al Khattab. The association banned new wells, as they would interfere with existing wells, and lobbied for the extension of the irrigation area.

Participatory Hydrological Monitoring (PHM)

The aim of PHM is to overcome lack of understanding of limitations to local groundwater resources and to achieve a common local agenda on groundwater management. PHM refers to a set of activities carried out to keep track of the changes in a hydrological cycle by the users themselves with little input from outsiders. The objectives of PHM are:

- Triggering a discussion at community level about rainfall, draft, water level and their relationship
- Evolving water use plans by the community based on utilizable groundwater resources
- To develop people-managed groundwater systems

Before getting started with PHM it is important to identify Stakeholders in Groundwater Management:
The farming community (men and women), drinking water users, other groundwater users, government departments, local government, watershed or water supply programs and possibly others.

Steps in the PHM process:

1. Preparation

- Reconnaissance/meeting with opinion leaders
- Awareness raising
- Delineation of watershed/aquifer system
- Water Resource Inventory

2. Setting up the monitoring

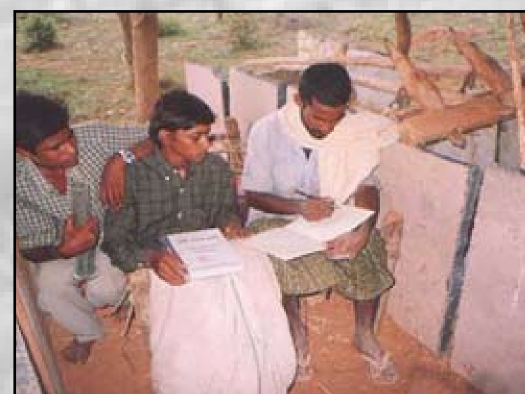
- Joint site identification: Rain gauge stations and observation wells
- Social feasibility study
- Procurement of equipment/material
- Establishing rain gauge stations and observation wells
- Supply of equipment to community

3. Getting the monitoring going

- Training farmers in monitoring
- Training farmers in data management
- Erection of display boards/data display

4. Crop water budgeting

- Rabi (= dry season) Resource Inventory
- Groundwater Availability Estimation at the end of Kharif (=wet season), using information from resource inventory and participatory monitoring data
- Collection of farmer crop plans
- Groundwater balance preparation for Rabi, using:
    - Expected demand on the basis of farmers' crop plans
    - Expected availability from inventory and monitoring data



Source protection through Rural Drinking Water Committees
Al Mawasit, Yemen

As part of rural water supply programmes, over the years many water supply committees have been established. They can play role in managing groundwater resources.

Drinking water management committees were established in the settlements of Al Dhuniab and Kareefah in 1992 and 1994, as part of a large rural drinking water programme. In both areas village networks were constructed, supplied from 30 m deep dug wells. The committees in both places performed outstandingly in managing the rural water supply system. Boards were systematically re-elected and business rules were regularly updated. Revenues were kept and maintained on special accounts and water rates for the local poor and health centres were reduced or even waived.

Since the completion of the schemes, water has been available 24 hours a day and occasional breakdowns have been solved in a timely manner. These committees had tremendous goodwill. Though they were established to manage the drinking water systems, the committees in both Al Dhuniab and Kareefah extended their scope to include the protection of the groundwater resource.

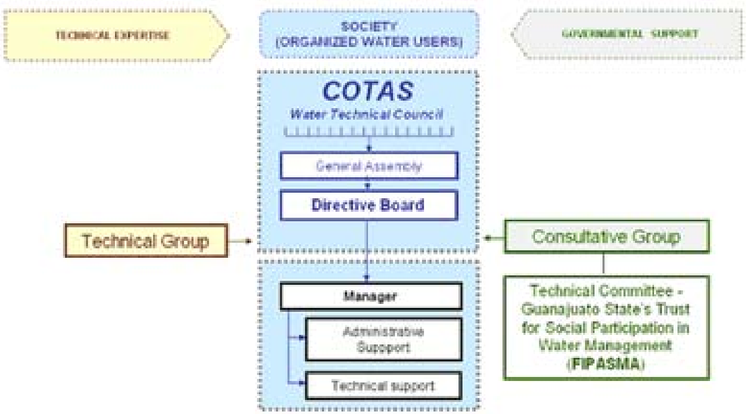
In Al Dhunaib, the project water committee issued a rule that no well could be drilled within one kilometre from the drinking water source. When one farmer attempted to develop a hand-dug well within the walls of his courtyard, he was pressurized by a village delegation to backfill the well. There were no repeated incidents after this. In Kareefah one local farmer was about to get an official permit to develop a well from the National Water Resource Authority (NWRA) under the provisions of the national water law. This greatly alarmed the Kareefah drinking water management committee, which suspected that any additional well in this area would jeopardize the drinking water system on which all livelihoods depended. The chairman of the Kareefah committee cajoled the local branch of the National Water Resource Committee to withdraw the permit.

Technical Groundwater Users Councils (COTAS)
Guanajuato, Mexico

The Technical Groundwater Users Councils (COTAS) of the state of Guanajuato are user-based groundwater management institutions which are formed by different groundwater users. The COTAS are organized as multi-stakeholder platforms to discuss sustainable groundwater use and have a general assembly and a directive board.

The COTAS have engaged in different activities such as water awareness campaigns, monitoring, technical assistance to the users - for instance on increasing irrigation efficiency. The COTAS, however, have no regulatory functions.

Funding for these organizations is currently provided by the state government through the State Water Commission of Guanajuato (CEAG) and through other funds from municipalities, government programmes, international funding institutions and the contributions of their members. Though in principle they could make a substantial contribution, at present they are limited to an advisory role, which limits their effectiveness.



Groundwater users monitoring committees
Jaral de Berrios, México

In the aquifer of Jaral de Berrios, Guanajuato, farmers' monitoring groups have been formed. These groups of farmers consist of 10-15 water users that unite in order to measure and report extracted groundwater volumes. In order to measure the extracted volumes the groups have been installing flow meters at the different wells. The extracted volumes are reported within the group twice a year. The data generated is collected by the Technical Groundwater Users Council (COTAS). The data from the different monitoring committees is processed by the COTAS for the whole aquifer. Once processed, the data is returned to the users of the monitoring groups.

Groundwater management districts
USA

Groundwater Management District Associations are in place in several parts of the United States. Their roles vary. The primary issue in Kansas, Colorado and Texas for instance is groundwater *quantity*, while in Nebraska it is groundwater *quality* and quantity. In Mississippi and Florida, Districts are responsible for the *joint management* of surface and ground water. *Subsidence* is the major issue in Louisiana and parts of Texas. Some of the Districts have developed unique projects in education and management to preserve groundwater resources for future generations.

Locally issued groundwater management rules and regulations
Nevada, USA

The Pumpkin Creek Basin Groundwater Management Sub-Area, established in 2001, has three purposes: protect groundwater quality, protect groundwater quantity, and provide for the integrated management of hydrologically connected groundwater and surface water. Backing these purposes is an elected executive board of directors and established management rules and regulations:

- Creation of a sub-area; clearly defined boundaries of the area of jurisdiction
- Permits to construct wells; these shall be required for every well, except those for domestic purposes
- Suspension of any further well development, exemptions being replacement wells
- Flow meters, all wells must install a flow meter
- Annual reports, each well operator should submit an annual

report containing: total amount of water used, purpose for the water, flow meter readings, and if for irrigation specification of the numbers of hectares for each crop
- Education: each operator is required to acquaint himself/herself with best management practices, with certificates valid for four years.
- Groundwater use may not exceed certified limits. irrigators may not irrigate land that is not certified, livestock operators may not exceed certified production capacity, other uses may not exceed the amounts allocated to them.

Groundwater users associations
Spain

Spain has a longstanding history of participation of irrigators in water management activities. Surface water irrigators associations have existed from as far back as the 11th century. The Water Act of 1985 created a similar framework for groundwater users associations. Since that time, 1400 groundwater users associations have been established. Some of these associations focus on water distribution, while others concentrate on collective management of aquifers. Numerous associations have been able to establish accepted rules regarding resource access and use. Moreover, by collaborating with the water authorities and local universities, the long-term sustainability of the resource has become an issue of shared responsibility.

Step well, Guadalquivir plains, Spain

6.3 REGULATION BY GOVERNMENT

In several countries the government is increasing its role in regulating groundwater by issuing laws and policies and, particularly at the municipal level, groundwater management plans.

Local government regulating new wells
Andhra Pradesh, Maramreddypalli, India

In the Nellore district in India, groundwater tables have declined significantly over the last 15 years except in the village of Maramreddypalli. In this village, the village government established a ban on new boreholes in 1995 after a severe drought. The rule was introduced after consulting the elders of the village and was also supervised by the village government. In 2001 a person tried to dig a hole in the middle of the night, but he was forced to stop by the villagers. After this incident no one has tried to make a borehole again.

Court system regulating groundwater rights

Colorado, USA

In Colorado an administrative and court system determine the rights concerning groundwater use. Potential well users must obtain a well permit from the State Engineer's Office (SEO). The SEO will investigate whether or not the well injures the vested water rights of others. Applications will be rejected if the groundwater flow is indicated as 'critical'. Only when the applicant can demonstrate a source of augmentation will the permit be given. The court system must ensure a legal right to utilize groundwater in Colorado's system.

Groundwater discharge permits to prevent the degradation of groundwater

Michigan, USA

Since 1994 it has been necessary to have a permit for discharging waste or waste water into the ground or groundwater for Executive Branch Departments and Sub-units. Applications for permits are viewed by the Department of Natural Resources. They determine whether or not the permit is given, based on hydrogeological studies. The process can take 90-360 days, depending on the complexity of matters.

Rule of capture or the rule of reasonable use

The rule of capture was issued in Texas in the first court case concerning groundwater in 1904 between Houston & Texas Central Railroad Co. v. East.5 In East, a railroad company dug a well in order to supply water for use in its locomotives and machine shops. The well, which produced 100,000 l of water daily, dried up the well of a neighbouring landowner, who used his well for household use. The court decided in favour of the railway company and issued the 'rule of capture'. Under the rule of capture landowners have the right to take all the water they can capture under their land and do with it what they please. They will not be liable to neighbouring landowners even if in so doing they deprive their neighbours of the water's use. The rule of capture is in contrast to "reasonable use", which provides that the right of a landowner to withdraw groundwater is not absolute, but limited to the amount necessary for the reasonable use of his land, and that the rights of adjoining landowners are correlative and limited to reasonable use. Since its adoption, the rule of capture has been widely criticized. Today, Texas stands alone as the only western American state that continues to follow the rule of capture.

The Punjab Groundwater Policy

Punjab is blessed with a huge underground reservoir of water. Its capacity far exceeds the combined capacity of all surface storages in the country. Unfortunately, groundwater is overexploited, water tables are dropping and water quality is deteriorating due to various reasons.
Proper attention should be given to groundwater management to prevent a crisis situation. In the Punjab Groundwater Management Plan the following policy actions are presented:

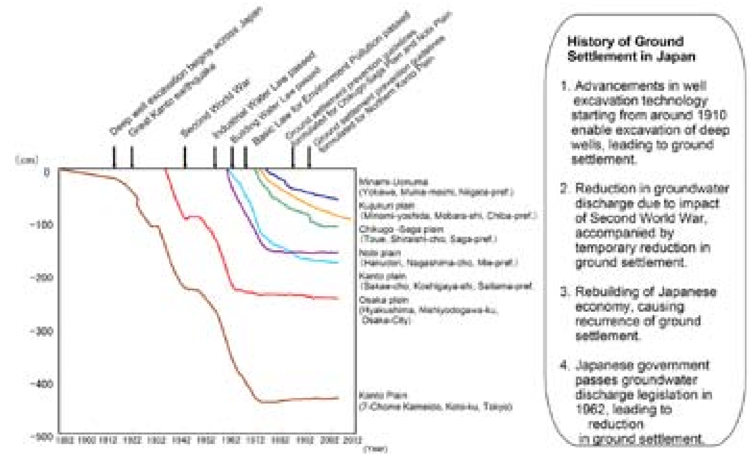
- Decide groundwater ownership rights
- Prioritize inter-sectoral groundwater uses
- Initiate process for comprehensive water act
- Fix operational range of groundwater reservoir
- Rationalize canal water allowances
- Revise gypsum marketing policy
- Strictly enforce EPA regulations to protect groundwater quality
- Strengthen water related institutions
- Prepare a drought contingency plan in view of climate change
- Start water management in pilot projects

Through appropriate policy and strategic actions, the current worrying situation can be reversed to preserve and improve the groundwater quality and to ensure its availability on equitable and sustainable basis.

Source: The Punjab Groundwater Management Plan (2007)

Controlling abstractions to stop land subsidence
Osaka, Japan

In Japan national governments passed various water abstraction laws from the mid 1950s and onward. This made it possible for the government of Osaka district to stabilize groundwater levels and counter land subsidence. In the previous decades land subsidence



amounted to more than two metres. As of 2007 the water abstraction levels in Osaka district were approved at 50-60.000 m^3/day, including the possibility of an additional abstraction of 2000 m^3/day. Groundwater levels in Osaka are projected to rise between 0.20-1.0 metre and ground subsidence is expected to be a thing of the past.

Groundwater preservation plan by city government
Kawasaki, Japan

The rapid economic and industrial growth in the city of Kawasaki bordering Tokyo bay has taken its toll. The ecological system including the natural water cycle had been severely disrupted. Excessive pumping of groundwater had caused subsidence, spring water had been drying up and surface water in rivers had become dramatically low. In the city council's plan to improve the urban environment completely, the city was divided into groundwater environmental divisions on the basis of characteristics such as geohydrology, water quality, land subsidence and the amount of abstraction wells. As such the most appropriate groundwater protection measures could be sought for each division. Divisions with suitable aquifers and water quality were designated as groundwater protection areas, with emphasis on the preservation of natural vegetation and the promotion of rainwater harvesting systems. In the overused divisions, prevention of further contamination was the main priority. In this area groundwater pumping was regulated and the prevention of negative effects of built-up areas was given attention.

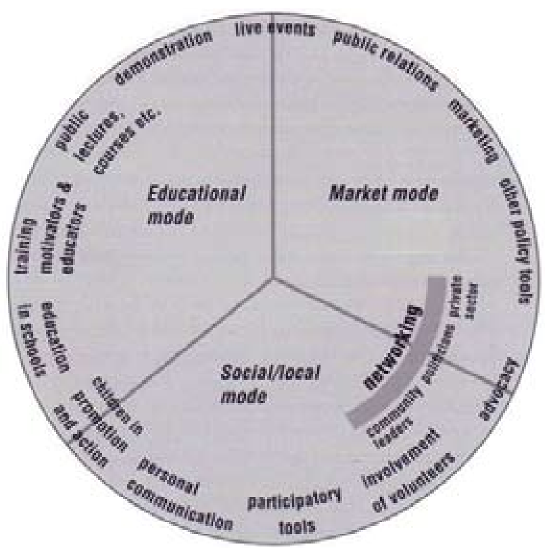
City government initiatives
Shanghai, China

In China, the Yangtze (Changjiang) is often likened to a "Dragon" because of its length and importance, and Shanghai to the Dragon's Head because of its location and its position in the national economy. However, this leading role has taken its toll. Whilst industries were booming so was the amount of groundwater that was being pumped. 200 million m^3 was abstracted in 1963 as newly developing industries required cooling in the summer. This resulted in rapid ground subsidence which measured a total 1.75 m from 1921 to 1965, locally reaching up to 2.63 m. The city government came up with a four-fold response. Firstly, it restricted groundwater pumping, particularly in the downtown areas. In 2007 the amount of water pumped was reduced to 40% of 1965 levels. The second measure adopted was to request water users to inject the same quantity of water into aquifers in winter as they pumped out in summer. Thirdly, the industrial use of groundwater was moved out from downtown to the suburbs and more water was taken from deeper aquifers. Fourthly, a monitoring network of land subsidence and groundwater levels was established, and a research centre was set up. This combination of measures proved successful. If the rate of subsidence in the 1960s had not been halted, large parts of the city would have been submerged in the sea.

7| CREATING GROUNDWATER AWARENESS

Overuse of groundwater, reduced flood water supplies and sand dune movement destroyed these once productive date palm groves in coastal Yemen

Groundwater is an invisible resource and the limitations and threats are often not well understood. Special efforts are required to create a basic understanding of aquifer systems and the actions required to use groundwater in a sustainable manner. A wide variety of awareness-creating methods can be used ranging from basic knowledge to detailed information to activities that actively engage water user groups. Often one event can be used to trigger another: a special groundwater running contest can be used to generate media publicity, so as to carry the message beyond the participants of the event.



Models for campaigning. Each mode has its advantages and opportunities that can be a unique contribution to the total mix of campaign strategies.

7.1 UNDERSTANDING THE CHALLENGE

Creating basic understanding
Exeter, Canada

In Exeter 90% of the population depends on groundwater supplied by five municipal wells and several private wells. The maximum capacity of the wells had been reached and to optimize the supply, conservation measures were taken. Five monitoring wells were drilled and contaminant sources were identified. Based on information from monitoring, recommendations for educational programmes were made.
In 2003 the education programme called "Exeter, a special place" came into action. The aim of this programme was to educate the citizens about the importance of protecting 340 hectare of groundwater recharge area. To achieve this goal, a brochure was made describing the objectives of the programme. Also, a series of four newsletters and a script for the local TV channel were written.

'Groundwater University'
USA

The Groundwater Foundation is an international non-profit organization with a mission to educate and motivate people about groundwater. The foundation organizes numerous programmes and events. They have set up, for example, an education camp called Groundwater University. This camp aims to connect students with water professionals. Every year in June, students from across the USA travel to Nebraska for three days of activities, field trips and presentations. The camp also organizes a youth groundwater congress for students between the ages of 10 and 15. For younger

children a festival called 'winning water' is organized where they can learn about water through indoor and outdoor activities.

Explaining a precarious situation
The Netherlands

The Dutch government set up a campaign called: 'Living with Water'. The aim of the campaign was to create broader understanding of the complexities of water management in the Netherlands. This was achieved through commercials on television and radio as well as advertisements in magazines, using a well-known presenter. The Netherlands faces challenges in dealing with the increasing risk of river floods, a lowering of groundwater levels and an expected rise in sea levels. The government intends to remind people of this precarious situation and emphasize that adequate responses are necessary, including alterations in landscapes, urban areas, housing development and groundwater retention.

Use an icon
USA

Icons are a powerful means of giving a 'face' to awareness campaigns. On the website of the Lower Platte South Natural Resources District, Wellhead Willy is introduced. Part of the website is especially reserved for children. Children can play online games that teach them about groundwater. One game is called "Keep the aquifer clean" where children need to help Wellhead Willy to keep potential contaminants away from the aquifer.

Engaging well owners directly
USA

During the annual national groundwater awareness week in the USA the National Groundwater Association encouraged well owners to check their well water in order to highlight the value of groundwater as a resource.

Theatre to draw crowds
Andhra Pradesh, India

In Andhra Pradesh, kalajatha, which is a type of rural folk art, was used to draw large crowds and convey the message of sustainable groundwater management. This was followed by intensive participatory hydrological monitoring (see chapter 6). A special theatre group was engaged to carry out a performance.

Kalajatha, a rural folk art, is used to draw large numbers and introduce the PHM activity, India

Engaging children in special groundwater days
Philadelphia, USA

The Carbon County Groundwater Guardians started in 2005 with a groundwater awareness day focused on children. During the event, children learned about groundwater by participating in activities such as constructing a watershed model, taking part in a relay race for water conservation, or examining organisms living in water. The first awareness day drew over 100 participants. This experience demonstrated that in many cases an effective way of reaching adults is through children.

Engaging large organizations
USA

The campaign to prevent spillage from motor oil was organized jointly by the National Water Resources Association and the Automobile Owners Association, as part of the National Groundwater Awareness Week.

Engaging politicians
India

By asking the incumbent Chief Minister to lend his photograph for a poster on water harvesting, his support to this activity was secured.

Role-playing game to discuss sustainable management practices
Republic of Kiribati

In the Republic of Kiribati in the central Pacific, the Public Utility Board and the Ministry of Works and Energy are applying innovative approaches to discuss groundwater usage. A computer-assisted role-playing game called Atollgame is part of this programme. Players of this game need to provide their family with sufficient water of good quality and have to make decisions about buying equipment, cultivating vegetables and they must also take the climate into account. With this game, dialogue will be facilitated which can result in sustainable management practices.

Groundwater awards
USA

Groundwater awards reward special services and efforts, but can also create publicity and raise the profile of groundwater problems. There are different organizations in the USA that provide groundwater awards to recognize noteworthy projects or contributions related to groundwater protection:

- The Groundwater Resource Association of California presents an award annually to a company or project in California.
- The Groundwater Foundation presents national awards every year to honour those individuals who create a legacy of groundwater protection through local action, education and government service.
- The National Groundwater Association gives an award to the best business practices, such as outstanding contributions, innovations or research.

Essay contests supporting special events
Phoenix, Arizona, USA

In January 2006, Disney on Ice invited schools in Phoenix to participate in a water conservation effort to raise awareness of water-saving measures. During this period Arizona experienced an extended drought. Students were asked to write essays on water-saving measures to increase awareness of water conservation. The two winners were asked to read their essays during the Disney on Ice Event.

7.2 UNDERSTANDING THE RESOURCE

Village transect walks
Andhra Pradesh, India

In cooperation with the Natural Resources Conservation Committee of Gram Panchayats (local government committee), training has been developed to increase awareness among community members. Part of this training was a village transect walk. The aim of the transect walk was to get a better understanding and raise awareness of the surroundings. People learn the location of village boundaries, where drinking water comes from, what crops are being cultivated by different people, and also what measurements others have already taken to improve groundwater management. During the walk, village maps were drawn, indicating tanks, wells and flood paths.

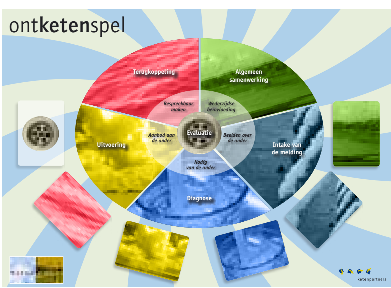
Animations
Spain

A computer animation programme was prepared for use by high school students, showing how a drop of water moves through different types of aquifers.

Animation programme for high school students

Chain game
The Netherlands

In the Netherlands a consultancy company named Chain partners developed a game about water to learn in a fun manner the different interlinked water uses and how the use of water in one sector affects another.



Educational groundwater level recorders
Tilburg, The Netherlands

In Tilburg in the Netherlands a project was started in 2002 where 15 educational groundwater level recorders, designed by an artist, were placed along cycling and walking routes. The aim of the recorders is to point out the importance of groundwater levels to passers-by. Next to every recorder, an information sign is placed. The left side of the sign gives an explanation of groundwater and the effect on soil moisture. The text on every recorder is the same, while the right side of the sign gives specific information on the local area. In 2005 these recorders were also set up in other parts of the Netherlands.

Using checklists on important topics
Australia

Linking the management of groundwater and surface water resources has become a primary target for the Australian government. Limitations in surface water availability have lead to groundwater development, yet these two sources are closely linked. In many cases the water available for consumption was accounted for twice, allocated both as surface water and as groundwater. The concern was that many water management plans did not account for stream-aquifer connectivity. A check list was prepared with key questions to provide water managers, water authorities, policy makers, catchment groups, industry groups with the tools to develop a consistent approach in conjunctive water management.

Emphasize the lesson learnt during a drought

Spain

In statistical terms the median annual precipitation is lower than the mean one, on the Iberian Peninsula. Dry periods have become more frequent, and the wet periods are more intense. The rainfall/drought statistics show that, although drought is an inherent climatic feature for Mediterranean countries, its timing is unpredictable. Mitigation measures to overcome the drought spells focus on the conjunctive use of ground and surface water, users and use analysis; and demand management measures. The Spanish government has had to change its exclusive policy of supply management (more dams, interbasin transfers and exploitation of new aquifers) to a greater emphasis on demand management (reducing losses in distribution networks, appropriate tariffs, mechanisms to avoid water wastage, “xeriscaping”, etc.).

Monitoring by well users

Irrigation district 66, Mexico

Having discovered that they overpumped groundwater, a small farmers’ group in Irrigation District 66 agreed to self-monitor

Holy springs

Many springs are traditionally considered holy places. This offers an important entry point to discuss the importance of protecting groundwater sources.

Holy well water from Lingam Mountain transported to the main temple of Vat Phou in Champasak, Laos

The myth of Aljawhara spring waters

Dhilmahmer, Yemen

As locals for centuries have benefited from its perpetual water, the inception of the spring of ‘Aljawhara’ is veiled by mythology. The story is that Haj Mohomed on his pilgrimage to Mecca received a package after a dream in which the Prophet had revealed himself and told Mohomed that he should open the package once back in his village of Dhilmahmer. While resting near the village on his walk back from Mecca, Mohomed decided to open the package. A gem (aljawhara in Arabic) suddenly fell out of the package onto the ground and turned into a spring. Since that day water has flowed from the spring. The water is used for ablution, as drinking water and for irrigation of village farms. A spring mythically gifted by a prophet thus represents the only real water source for the village of Dhilmahmer.

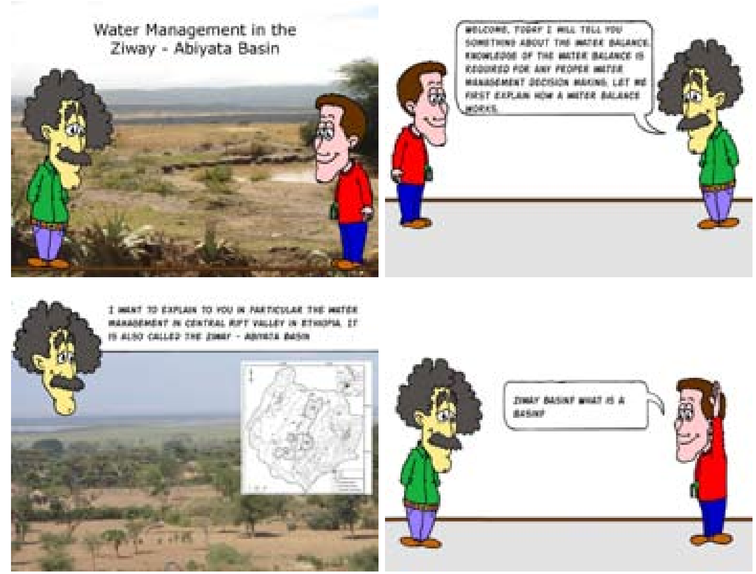
their groundwater use. In an area where agriculture uses 90% of the groundwater, the farmers aimed to understand the local groundwater resources as well as the limitations. Having installed volumetric water meters on each pump and kept records, they succeeded in spreading the initiative throughout the district, resulting in full coverage and sufficient data for attuning resource availability and abstraction.

Farmer field schools

In an effort to 'demystify science' and make groundwater management common knowledge, farmer field schools have been pioneered by the Andhra Pradesh Farmer Management Groundwater System Project.
Farmers meet every 15 days to discuss topics such as hydrological measurements, water recharge, water availability and appropriate cropping systems, water-use efficiency, organic farming methods, institutional linkages, gender issues in water management, and the impact of HIV/AIDS on the farming sector. Over 2000 lead facilitators have been trained through the project. They will conduct more than 1000 farmer field schools of 15 sessions each in a year, aiming to reach 800,000 farmers.

Cartoons used as a communication tool in the analysis of water management
Ziway , Abiyata Basin, Ethiopia

The results of an analysis of the water management in the Ziway, Abiyata Basin were summarized in the form of a cartoon book. The pointed visual communication made it possible to explain a complex story in fifteen minutes. By using two characters that were asking and answering questions and using a combination of cartoons and photographs, a lively dialogue was created.

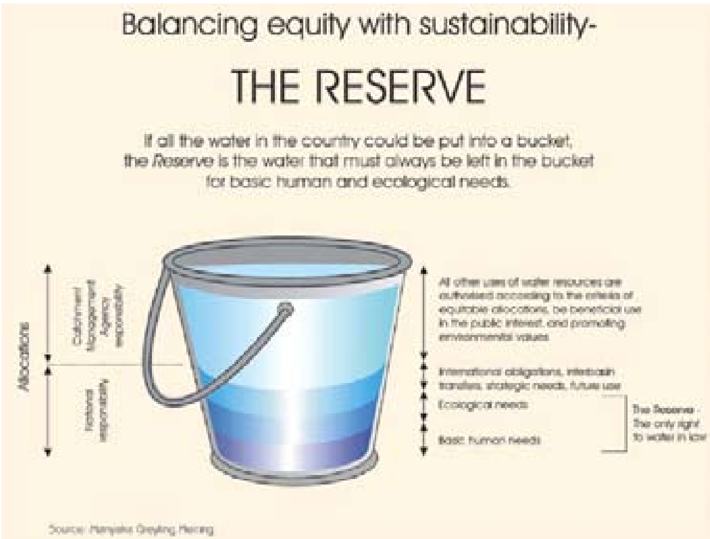


Cartoon on water management in Ziway, Ethiopia

Using strong unifying concepts

To simplify complex topics and ensure they can still be publicly debated, strong unifying concepts can be used. One example is the 'Reserve'. 'The Reserve' aims to make the point that there is a minimum level of water resource protection that will assure sustainable supply for the future.
It provides a set of rules to prevent rivers, estuaries, wetlands and groundwater from being overused. Water resources provide a

number of essential products and functions. If water resources are polluted or overexploited, these vital services will not be available in the long run.
In the bucket in the figure, the Reserve consists of ecological and basic human needs that need to be protected and safeguarded at any cost. All other water uses are authorized according to equitable allocations.



7.3 AWARENESS AND ACTION

The challenge of awareness raising is the connection with action. There is a risk that just highlighting issues and problems over time leads to a lack of interest or opposition. In general, there are many actions that can be undertaken and it is useful to inform and encourage players on how these can be carried out. A special case is the use of legislation. In many countries there are laws and ordinances on groundwater, yet they are not known to anyone – either the general public or legal professionals, so at best they are used arbitrarily. Legal awareness can make a large contribution to operationalizing laws and to groundwater management.

Bringing home groundwater legislation
Andhra Pradesh, India

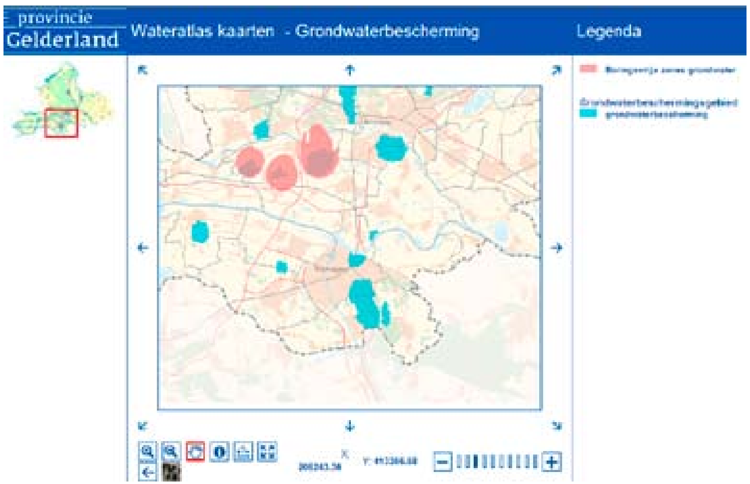
In Andhra Pradesh, India, the content of the Andhra Pradesh Water, Land and Trees Act was widely discussed in a training programme on local groundwater management. This training took place in 970 villages (gram panchayats) that had been the most affected by depleted groundwater tables. The discussion familiarized water users with the scope and need for groundwater protection under the new law. The success of the awareness-raising activities was that the new law was no longer seen as 'alien' by farmers, but instead was considered a tool to support local management of vulnerable water resources. When the Act was enforced in 2004, there was no resistance from groundwater users. Instead, it was the drilling rig operators, who had not been consulted and educated, that vehemently protested and went on strike.

Drilling rig operators on strike, protesting against the Water Act of Andhra Pradesh, India

Maps supporting legislation

The Netherlands

In the Netherlands, the Ministry of Transport, Public Works and Water Management is in charge of large watercourses. The smaller, generally non-navigable surface waters are the responsibility of water boards. Groundwater is the responsibility of the provinces and municipalities. The Netherlands Guideline for Soil Protection aimed to unify and harmonize licencing regulations. The regulations include the delineation of groundwater protection areas and restrictions on certain land uses. Provinces, municipalities and water boards organize information-sharing meetings with other stakeholder groups. For example, the province of Gelderland has maps of protection areas prepared and displayed on durable signboard throughout the Province.



Map of the Province of Gelderland, the Netherlands

Controlled action messages disseminated through audiocassettes

Maharashtra, India

Part of the Total Sanitation Campaign involved distributing audiocassettes. These cassettes had local folk songs promoting the concept of sanitation. Various methods were used during this campaign, but the audiocassettes were the most popular.

Public action for cleaner water

Tamilnadu, India

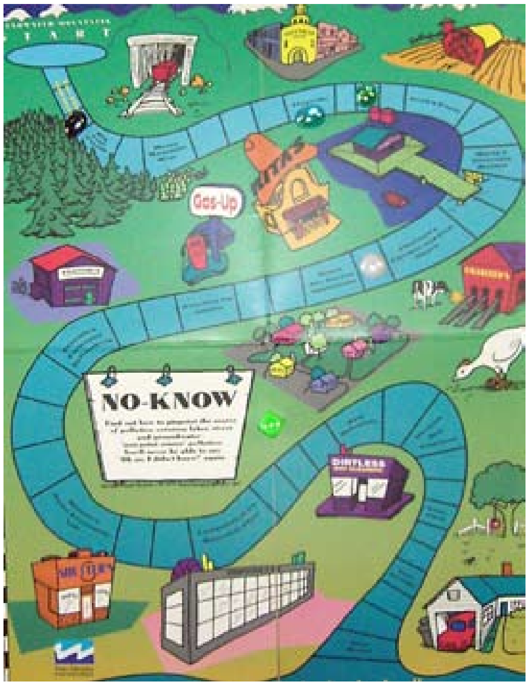
Effluents discharged by the South India Viscose industry in the Bhavani River caused great stress on surface and groundwater sources. Contaminant levels were so high that industries and households have had to resort to sources elsewhere. In cooperation with the local Peace Trust, a joint front was mobilized to oppose pollution by the industries. The Peace Trust launched a publicity campaign which included using stickers, slides, graffiti, posters, billboards, an environment monthly magazine, and a capacity building programme on environmental law. In addition, a march for environmental protection involving local organizations and the public was organized. The joint front also lobbied members of parliament and the assembly, religious leaders and judicial officials and provided legal aid.

Water Audit Kit and Conservation Helpline to improve efficiency at home

Nevada, USA

The Southern Nevada Water Authority provides indoor test kits.

This kit includes several objects such as: installation instructions, water-saving showerheads, thread sealing Teflon tape and a toilet diverter.
Conservation Helpline – The Southern Nevada Water Authority established a conservation helpline at (702) 258-SAVE (7283). Calls to this helpline can be made to request water-saving publications and information on the conservation programme, and it is also possible to ask questions about drought restrictions.



Board game called 'No Know'. Find out how to pinpoint the source of pollution entering lakes, rivers and groundwater (Water Education Foundation)

Using different types of posters

Participatory setting, open interpretation posters
The Artists Development Workshop (Pakistan) argues that posters in a participatory setting should be open for interpretation, in order to invoke discussion and lead to creative thinking.

Educational posters
Often posters have a lot of information and interesting details. They are meant for a closer look.

Promotional posters
Promotional posters are clear to the viewer at a glance and they usually have one large slogan and few details.

Example of an educational poster on groundwater management in Andhra Pradesh, India

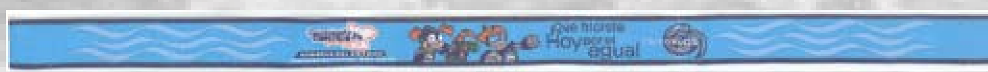
Source: Ideas for Water Awareness Campaigns, 2002.

Hidrokids

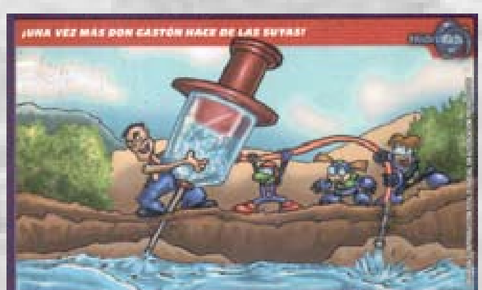
In Mexico a large project has been set up to create awareness on the groundwater situation in Guanajuato. This project is aimed at children. A variety of promotional material is used: cartoons, cards, bracelets, games, stickers, etc.

Hidrokids – stickers

Hidrokids - cartoon



Hidrokids – bracelet



Hidrokids - cards

Water games on the internet

There are by now a large number of water games on the internet. A small sample is given below:

Links to English internet sites
Water Science for schools (USGS)
http://ga.water.usgs.gov/edu/
Water Quiz (UN)
http://www0.un.org/cyberschoolbus/waterquiz/waterquiz4/index.asp
Water Year 2003 (UN)
http://www.wateryear2003.org/en/
Freshwater Fury
http://www.e-magination.org/freshwater/freshwater1.htm
Droplet and the water cycle (NASA)
http://kids.earth.nasa.gov/datwc.html
Drinking water and groundwater kids stuff (EPA)
http://www.epa.gov/safewater/kids/gamesandactivies.html
The Great water Odyssey
http://thegreatwaterodyssey.com/games.html
Melbourne Water Education
http://education.melbournewater.com.au/

Links to Spanish internet sites
Ploppy en Espana
http://ploppy2.alcaraz.com/
Hidrokids en Mexico
http://hidrokids.guanajuato.gob.mx/
La Cienca del Agua para Escuelas (USGS)
http://water.usgs.gov/gotita/
El Reparto del Agua (CAM)
http://www.aguacam.com/multimedia/juegos/reparto_agua/juegoAgua.html
Planeta Azul
http://www.asac.es/aigua/cast/1.htm
El Ciclo del Agua (con ejercicios)
http://platea.pntic.mec.es/~iali/CN/elciclo.htm#

8| GROUNDWATER MANAGEMENT: SPECIAL CASES

During the 1999-2003 drought water logging disappeared in large parts of Sindh, Pakistan and SCARP drainage tube wells were used for irrigation

This chapter discusses a number of special cases of groundwater management. First, information and case studies are provided on the conjunctive use of groundwater and surface water, which often supports productive farming systems. The second special case is the management of transboundary groundwater – an increasingly important phenomenon. Thirdly, the management of groundwater on small islands is discussed. The survival of many populations on small islands depends on adequate management of groundwater. The last specific case that is highlighted is groundwater management in areas with saline groundwater. Communities in these areas are often the worst off as they have no access to useable water for drinking or other uses.

8.1 CONJUNCTIVE MANAGEMENT IN LARGE IRRIGATION SCHEMES

In many surface irrigation systems a system of conjunctive use has evolved. Supplementary irrigation using groundwater resources has become common practice. This groundwater originates from seepage from canals and excess field irrigation deliveries. A very efficient system has developed whereby all canal losses are reused through pumping from the underlying shallow aquifers. There are now many calls to move from conjunctive use to conjunctive management, so as to maximize water productivity.

Conjunctive use instead of waterlogging
Punjab, Pakistan

When inexpensive locally manufactured diesel pumpsets ('Peter' engines) came on the market in the 1980s, the use of groundwater increased dramatically in the large surface irrigated area of Punjab in Pakistan. By now there are an estimated 700,000 diesel pumpsets in Punjab and they provide more than 50% of the water at farm gate in the world's largest irrigation system. The use of groundwater has made waterlogging all but disappear in the fresh groundwater zones. It is estimated that the entire increase in farm yield in the last two decades should be attributed to conjunctive use of groundwater and surface water.

Wells constructed next to irrigation channels in areas with saline groundwater. The wells tap the seepage from the irrigation canals that is less salty, Afghanistan

Groundwater use stimulated by reduced canal supplies
Bhakar, Pakistan

Large parts of Bhakar District have become waterlogged as a result of canals with an overabundant water volume. A new supply schedule was introduced for the Thar Canal, where water was delivered via the canal for only two out of three weeks. Consequently, farmers sought recourse to supplementary groundwater irrigation. A reduced volume of water in the canal coupled with intensive use of groundwater brought the water system back into balance and waterlogging disappeared.
The examples of conjunctive use, such as in Bhakar and Punjab, suggest that the volume of water stored in canals for irrigation

needs to be revisited to avoid unnecessary waterlogging in some areas and encourage extra recharge in others.

Recharging groundwater in the monsoon period
Uttar Pradesh, India

The University of Roorkee has undertaken a ten-year experiment in channelling surplus river flows through the unlined channels of the Madya Ganga Canal during the monsoon period. These monsoon flows recharge local aquifers. During the dry season, the stored water is used by farmers for a second crop. The draw down of the aquifers during the dry season helps to maximize their water storage potential during the subsequent monsoon period. The recharge also secures an irrigated dry season crop, reduces pumping costs and stabilizes groundwater tables. The University of Ludhiana is working along similar lines, exploring the potential of disused drainage canals to recharge groundwater tables during monsoon flows.

Requisition tube well water to augment canal supplies
Mazandaran Province, Iran

In coastal Iran, water is used from surface canals, large rainwater storage ponds and groundwater. During periods of low river flows, water can be requisitioned from tube wells under a local arrangement to augment supplies in the irrigation canals.

Conjunctive water use in Mazandran, Iran. The area used to be waterlogged. The proliferation of small diesel pumps lowered the water table and provided irrigation water at the same time.

Avoid blocking subsurface flows
Wadi Siham, Yemen

The Tihama has transformed into Yemen's breadbasket due to a highly productive resource system, where spate irrigation (irrigation using flash floods) and groundwater irrigation are combined. However, care is required when constructing diversion works. A cut-off weir on Wadi Siham blocked the sub-surface flow in this dry river and caused tens of wells downstream to dry up.

Small water retention measures
Water Management Project, Central Benelux

Small weirs have been placed on the rivers and canals flowing through a sandy area on the border of the Netherlands and Belgium. The weirs help to retain water for agriculture, recharge groundwater tables and restore natural vegetation. Local farmers and water boards decide the location of the weirs. Other water retention measures, such as closed culverts and canal beds, are less popular. Unlike the weirs, these measures do not allow farmers to manage their own groundwater levels.

8.2 TRANSBOUNDARY GROUNDWATER MANAGEMENT

The importance of transboundary groundwater management is increasingly being recognized as an important issue. Transboundary aquifers are being studied, monitored and assessed, by a number of organizations including ISARM (Internationally Shared Aquifer Resource Management), an organization led by UNESCO. A first transboundary aquifer authority has been established, and transboundary groundwater is also increasingly incorporated into the work of international river basin committees.

Joint studies and dissemination

Argentina, Brazil, Paraguay, Uruguay

Between 2003 and 2007, "Environmental protection and sustainable development of the Guarani Aquifer System (GAS)" project has been working in four countries (Argentina, Brazil, Paraguay and Uruguay) to create sustainable management and use of GAS in the four countries. The project focuses on enhancing technical knowledge, establishing well-monitoring networks and developing a proposal for a management framework. Moreover, an internet site has been developed in Portuguese, Spanish and English which is intended to raise public awareness and involvement. The site includes educational materials, films and games for children, technical manuals on tube wells and the aquifer, and seminar and workshop announcements. The public domain is thus used to connect the Guarani Aquifer countries in their joint goal to sustain their groundwater resources.

Monitoring guidelines for transboundary water

In 2000, the UN/ECE task force developed Guidelines on Monitoring and Assessment of Transboundary Groundwaters. The importance of developing transboundary guidelines was addressed in the convention 'Protection and use of transboundary watercourses and international lakes' (1992).
The guidelines are based on a monitoring cycle (see figure). Each chapter discusses at least one of the topics represented in this scheme.
Some key points of the guidelines:

- Functions, pressures and targets of transboundary aquifers should be identified and priorities should be set.
- Proper identification of information needs requires that the concerns and decision-making processes of information users are defined in advance.
- Monitoring strategies should serve as a guide in establishing realistic monitoring priorities, not only in terms of what should be monitored and where, but also in terms of timing and funding.
- Ranking and sectioning areas where potential pollution sources are located, or where groundwater use is high, will make the programme more effective.
- Data produced by groundwater monitoring programmes should be validated, stored and made accessible. The goal of data management is to convert data into information that meets the specified information needs and the associated objectives of the monitoring programme.
- Quality management comprises the definition of a quality policy and a quality system.
- The successful drawing-up and implementation of policies, strategies and methodologies on groundwater management crucially depends on institutional aspects.

Monitoring cycle used in Guidelines on Monitoring and Assessment of Transboundary Groundwaters

European Directive for cleaner groundwater

EU

In December 2006, members of the European Parliament approved new legislation that should improve groundwater quality through implementation of much stricter measures against pollution by preventing 'hazardous substances' such as cyanide, arsenic, biocides and phytopharmaceutical substances seeping into aquifers.

The scope of the directive was broadened so that its aim will now be to protect groundwater 'against pollution and deterioration' and not only 'against pollution'. Member States will be required to take 'all measures necessary to prevent inputs into groundwater of any hazardous substances'. The measure is particularly important because in many areas groundwater is the largest source of public drinking water and aquifer systems extend beyond national borders. Member States will have two years to translate the directive into national law. These laws should then come into effect from early 2009.

International Groundwater Law in the making

In 1970 the United Nations International Law Commission (UNILC) was given the task of formulating an international tool for clarifying and codifying the international law applicable to non-navigational exploitation of international watercourses. Even though, after more than 25 years work, this attempt was positively acknowledged by the 1997 United Nations Commission on the Law of Non-Navigational Uses of International Watercourses, there was still no focus on the international law governing transboundary groundwater resources. This started to change in 2002, when the UNILC started to expand its focus, extending this to the law relevant to transboundary water resources, a topic dubbed as "shared natural resources." This resulted in a thorough study of the law, science and policy of groundwater globally, executed mainly by Ambassador Chusei Yamada. His efforts laid the groundwork for formulating the nineteen Draft Articles on the Law of Transboundary Aquifers. These Draft Articles were prepared by the UNILC's Drafting Committee, which were adopted in 2006. States had been invited to present comments on the UNILC Draft Articles by January 2008. Subsequently the UNILC will prepare and submit a revised set of articles to the UN General Assembly. These are to form a basis for negotiating and adopting a global instrument on international groundwater law.
19 Draft Articles have been formulated:

Introductory Draft Articles on Scope and Definitions;

Draft Article 1 Scope
Draft Article 2 Use of Terms

Draft Articles on General Principles;

Draft Article 3 Sovereignty of Aquifer States
Draft Article 4 Equitable and Reasonable Utilization
Draft Article 5 Factors Relevant to Equitable and Reasonable Utilization
Draft Article 6 Obligation Not to Cause Significant Harm to Other Aquifer States
Draft Article 7 General Obligation to Cooperate
Draft Article 8 Regular Exchange of Data and Information

Draft Articles Related to Principles on Protection, Preservation and Management;

Draft Article 9 Protection and Preservation of Ecosystems
Draft Article 10 Recharge and Discharge Zones
Draft Article 11 Prevention, Reduction and Control of Pollution
Draft Article 12 Monitoring
Draft Article 13 Management

Draft Articles on Activities Affecting other States;

Draft Article 14 Planned Activities

Miscellaneous Draft Articles;

Draft Article 15 Scientific and Technical Cooperation with Developing States
Draft Article 16 Emergency Situations
Draft Article 17 Protection in Time of Armed Conflict
Draft Article 18 Data and Information Concerning National Defence or Security
Draft Article 19 Bilateral and Regional Agreements and Arrangements

The Nubian Aquifer Joint Authority
Libya, Egypt, Sudan and Chad

Libya, Egypt, Sudan and Chad share the Nubian Sandstone Aquifer and have formed a Joint Authority to manage the resource. As one of the first authorities of its kind the four states initiated and bestowed the joint authority with certain powers to govern use of the aquifer including:

- Preparing and executing studies, in particular, related to the environmental aspects of groundwater development, desertification control and energy;
- Collecting and analysing information;
- Developing and executing a common policy, programmes and plans for the development and utilization of the groundwater resources;
- Establishing cooperation and disseminating information on the Nubian Sandstone Aquifer System.

Each Member State appoints three ministerial level parties to a Board, and the Board manages the Joint Authority.

8.3 GROUNDWATER MANAGEMENT FOR SMALL ISLANDS

In small islands, groundwater is an extremely vital resource. Overuse can lead to shortage and salt water intrusion. Pollution can undermine public health in a dramatic way. Managing groundwater on small islands is more important than anywhere else.

Recommended practices for sanitation on small islands

Sanitation can be a major cause of groundwater pollution on small islands. The following measures are recommended to avoid this:

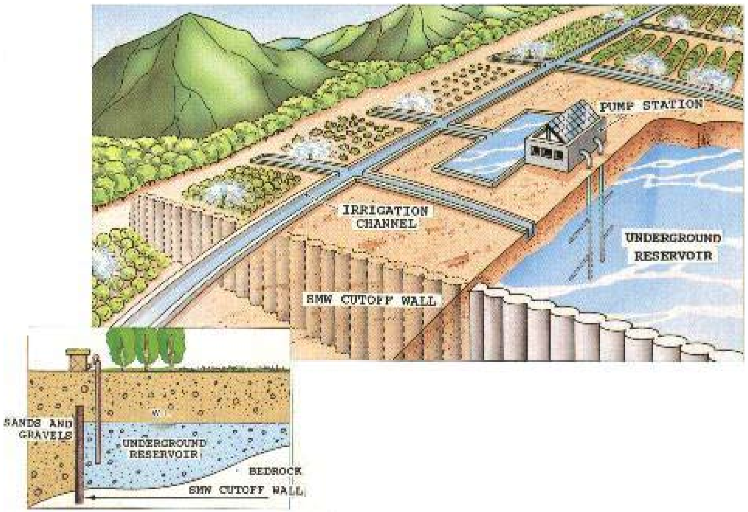
- Providing public information on the link between sanitation and drinking water quality
- Planning regulations to restrict population density in unsewered areas
- Developing public health regulations on design and maintenance of sanitation systems
- Specifying well-head zones
- Establishing monitoring procedures for pathogens and nitrogen in drinking water supplies and developing contingency plans in case water does not meet the required quality
- Disinfection of water supply wells and/or finding alternative supplies (rainwater tanks)
- Establishing centralized water supply and sanitation systems

Source: P. Dillon (1997), Groundwater pollution by sanitation on tropical islands. Paris: UNESCO-IHP.

Using a combination of measures
Malta

The renewable groundwater potential on the Maltese Islands is estimated at being close to 40 million m^3/year. In order not to cause salt water intrusion, only 15 million m^3/year of groundwater can be extracted. Nonetheless, in 1995 approximately 23 million m^3 was used. A combination of measures have been undertaken to balance water supply and water demand. First, in order to retain storm discharge, a large number of small dams have been constructed across drainage lines. Open reservoirs have been constructed along recently made roads to minimize run-off. Total dam capacity is estimated at 154,000 m^3.

At present 31.4 million m^3/year of desalinated water is produced from four sea water reverse osmosis plants and one brackish water plant. An increasing portion of the wastewater is treated and reused.



Cut-off wall preventing saline intrusion, Japan

Sub-surface dam for groundwater retention and prevention of salt water intrusion
Japan, Nakajima Island

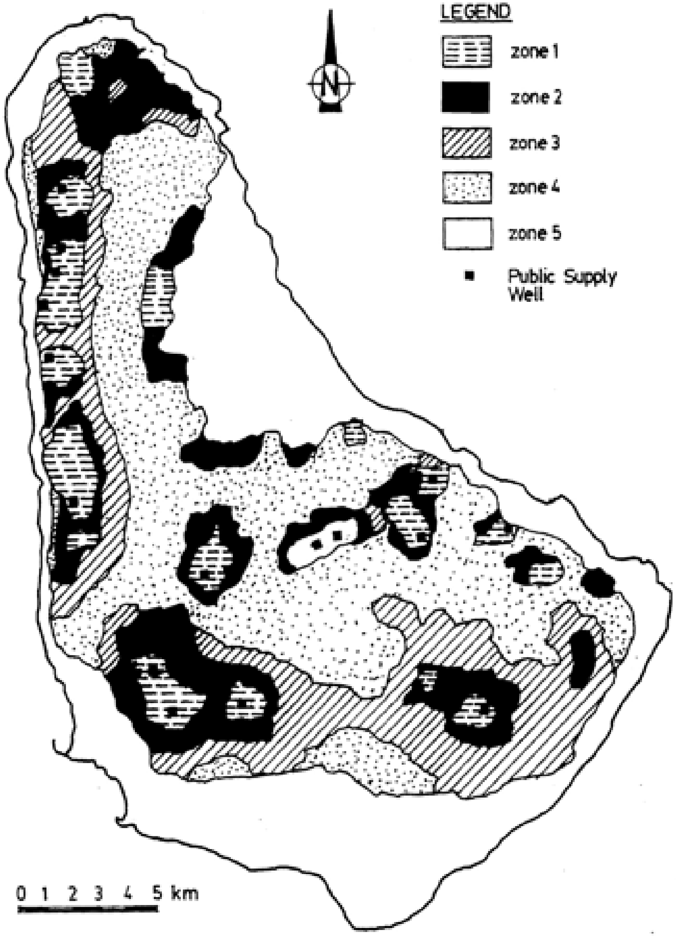
The Nakajami Island in Japan has a small watershed and the possibilities to use surface water are limited. On the island a sub-surface dam was constructed initially as a test dam for numerous purposes. One of the purposes of the dam was to study methods for protecting and monitoring groundwater quality.

Principal features of development control zones in Barbados

Zone	Definition of outer boundary	Maximum depth of soakaway pits*	Domestic controls	Industrial controls
1	300-day travel time	None allowed	No new housing. No changes to existing waste-water disposal.	No new industrial development
2	600-day travel time	6.5 m	Septic tank of approved design, discharged to soak away pits Separate soak away pits for toilet effluent and other domestic waste water. No storm run-off to sewerage soakaway pits. No fuel tanks.	All liquid industrial waste to be dealt with as specified by water Authority and maximum soakaway pit depths as for domestic waste
3	5-6 year travel time	13 m	As above for domestic waste-water. Fuel tanks to approved leak-proof design	
4	Extends to all high lands	No limit	No restrictions on domestic waste-water disposal. Fuel tanks to approved leak-proof design.	
5	Coastline	No limit	No restrictions on domestic waste-water disposal. Siting of new fuel storage tanks subject to approval of Water Authority.	

* Soakaway pits are excavations down to fissures, designed to provide most rapid disposal of water.

After the pumping tests, it was also established that the dam retained
groundwater, making it possible to pump, whilst at the same time preventing salt water intrusion.



Protection zones

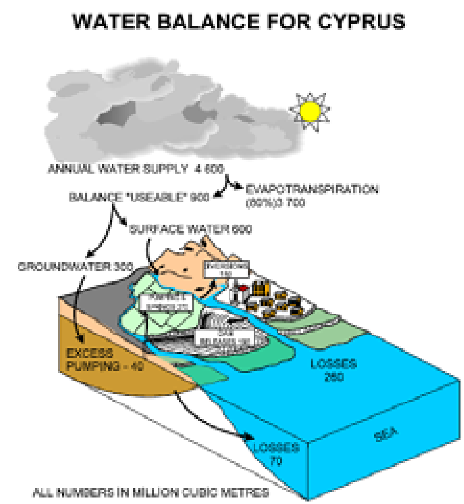
Barbados

The Caribbean island of Barbados depends almost totally on groundwater. Safe water supply is very important for the island for public health reasons, but also for economic reasons. Tourism is one of the main economic activities in Barbados, and the hotels on the island use a lot of water. Flow rates in the island aquifer are rapid and pollutants or salinity could rapidly contaminate most available supplies. In 1963 the vulnerability of the aquifer was recognized and resulted in the announcement of five control zones in which different rules are set (see figure and table).

Rationing agricultural supplies

Cyprus

After a third consecutive year of low rainfall, the government of Cyprus has had to initiate measures to deal with both the short-term and long-term problems. More than 80% of Cyprus's annual precipitation returns to the atmosphere through evapotranspiration, leaving a balance of 900 million m^3 for



use on the island. Dam reservoirs were getting empty and in 2007 the government decided to ration the supply of water to farmers. For seasonal plants, such as potatoes, water was provided until May 1 only. Water supply to perennial crops was reduced to a survival minimum of 40%. Greenhouses were provided with 50% of their requirements. There were no cuts for livestock breeders. In the long run the government of Cyprus wants to reduce water demand through full-cost recovery on desalinated water, lowering of subsidies on irrigation water, a change in cropping patterns, formation of underground strategic reserves and increased use of recycled water.

Restoring recharge wells
Port Blair, Andaman Islands, India

Dug by the Japanese army in World War II 54 of the existing 191 wells in Port Blair have been cleaned up and are ready to store water. Relying on rainwater for most of its drinking water Port Blair was not able to catch sufficient amounts from the 3000 mm of rain that pour down annually. An undersized water reservoir, but also unusual erratic rainfall has forced the Municipal Council to restore the wells which remarkably still carry water. In the long term, the islands' government will have to search for more rainwater harvesting options. The wells however have in the meanwhile proven their worth in Port Blair's water capture struggle.

Native land owner rights and groundwater use
Fiji

In Fiji there is a notion that 'water needs to be fixed', and that proper legislation is required in order to curtail some of the problems with water. Two important issues have been identified in Fiji that require water legislation for resolution, these being:

- the establishment of a clear legal power to enable the government to allocate water for all purposes and from all sources, and
- the control of surface water allocation and groundwater allocation.

However, in Fiji there is still a discussion going on regarding native land owner rights, and whether these rights should be extended to water use. The general view appears to be that land ownership should be accompanied with rights over water associated with that land, implying water that occurs on or under the land (groundwater). This may imply that land owners would receive some form of compensation for water extracted from their land. This has resulted in two questions:

- Should native landowners have the authority to decide who may or may not exploit water that flows past, through or under their land, and
- Should a user pay compensation to native landowners when they exploit water that flows past, through or under the land of the latter.

8.4 GROUNDWATER USE IN SALINE GROUNDWATER ZONES

Large parts of the world are underlain by saline groundwater zones. These areas are among the most problematic in securing a safe drinking water supply. Drinking water is obtained from surface water or from small freshwater lenses near to river or canal banks. With water supplies being so precarious, contamination of surface supplies can have enormous consequences for public health. Also the interruption of surface supplies – for instance for irrigation canal maintenance – will have immediate repercussions in drinking water availability and recharge of the lenses.

Drainage improving drinking water availability
Central Punjab, Pakistan

The Drainage IV project in Central Punjab implemented a series of drainage measures, both sub-surface and surface drains, to restore the agricultural productivity of this heavily waterlogged area. Intriguingly, people in the area assessed the largest benefit from the drainage works to be the improvement of local drinking water supplies. Prior to the drainage improvement the area had very high saline groundwater tables. With the drainage works the water table lowered, creating storage space in the shallow aquifers. A thin lens of fresh/brackish water formed on top of the saline groundwater, fed by rainfall and irrigation water seepage. This water lens, though still of marginal quality, was an enormous improvement over the earlier drinking water supply, which required women to travel very long distances, particularly in the dry season.

Using brackish water for agriculture and creating buffers for recharge
Hebei Province, China

In an attempt to overcome the spring drought period, the county of Nanpi decided to pump brackish/saline groundwater and divert river water in order to balance the quality of water. As upstream users extracted more and more water from the river, less was available for the downstream users in Nanpi County. Groundwater became a last resort. The Hebei Institute of Hydrotechnics developed the technology of using brackish and semi-saline water for watering crops during drought periods The Institute also promoted the development of drainage so as to create a buffer in the shallow aquifer that could be replenished by freshwater rainfall infiltration as well as from river and canal seepage. A sustainable equilibrium was found to sustain agriculture in Nanpi County.

Rainwater harvesting for drinking water
Coastal India

In many parts of coastal India groundwater is highly saline and unusable. In several places improved rain water harvesting ponds were constructed. These use PVC or geotextile linings, covered by a layer of soil. Sand filters are installed to reduce the amount of pathogens in the drinking water.

Aquifer Storage and Recovery Wells (ASR)
The Netherlands

Aquifer Storage and Recovery is a method of storing a pumped surplus of water in an aquifer, and then pumping it out when needed.
In the western part of the Netherlands this method is used to irrigate greenhouse vegetables and flowers. In this part of the Netherlands, surface water can not be used for irrigation purposes because it is too saline. Groundwater cannot be used either because it is brackish.
ASR wells are injected with rainwater, collected from the roofs of the greenhouses, at a depth between 15-50 m. The stored water is used to irrigate the vegetables and flowers. Since 1983 over 100 installations have been built, which in generally operate successfully.

Fish ponds using saline groundwater
Australia

Australia is experiencing a growing problem of dryland salinity, which is of particular concern to its rural industries. Land affected by salt typically has shallow saline groundwater tables with varying degrees of salinity. In 2002 the Centre for Natural Resource Management (CNRM) proposed a method which enables the exploitation of saline groundwater, thereby dropping the level of aquifers, and remediating affected land through an aquaculture-based salt interception system. Saline groundwater was shown to be suitable for the culture of snapper, black bream and King George whiting.

Capturing water from a submarine spring
Argolikos Bay, Greece

In the Mediterranean Sea many submarine springs have been detected. Near the coast of Greece at a depth of 72 m is the Aqualos spring. The submarine groundwater discharge can function as a freshwater source. The water provided can easily be captured and even if the discharge is not completely fresh it is cheaper to desalinate this water than sea water.

ANNEX 1| GLOSSARY

Sending soil and manure to groundwater irrigated areas, Senegal

Abstraction of water – The process of taking water from any source.

Aquifer – A water 'reservoir' of porous media (usually sand, gravel or limestone).

Brackish water – Water which has a salinity between fresh water and sea water. It is saltier than fresh water, but not as salty as ocean water.

Compaction – Compression of soil, causing a reduction in pore space. This leads to poor drainage and poor gas exchange. In a very compacted soil, tree roots are not able to grow.

Confined aquifer – An aquifer that is bounded above and below by restricting layers. Confined aquifers are usually under pressure.

Depletion – When withdrawal of water, either from groundwater or from surface water reservoirs, is larger than the rate of recharge.

Discharge – Volume of water transported by a river in a certain unit of time.

Dug well – Well made by digging a hole in the ground. Usually no special equipment is required for the construction.

Electrical Conductivity – Ability of water to conduct an electrical current. EC is used as an indication of the amount of salt dissolved in water. The more salt, the higher the EC.

Evapotranspiration – The process of water drying up into the air from soil and water surfaces, combined with water used by plants.

Geotextile – A product made from synthetic fibres that are woven, knitted or matted together.

Groundwater – Water that is stored in a porous media (like soil, sand or gravel) under the soil surface.

Groundwater table – Top of an unconfined aquifer.

Hydrogeology – Refers to the area that deals with distribution and movement of groundwater in the soil and rocks of the earth's crust.

Karst – Limestone or dolomitic region characterized by sinkholes, caves and underground drainage.

Landfill – Large outdoor area where solid waste on land is disposed of.

Mulching – Type of soil management where a covering layer is applied on the soil usually to reduce water loss, protect from cold and suppress weeds.

Overexploitation – When withdrawal from the water source is larger than replenishment.

Permeability – The ability of material to transmit fluid through porous spaces.

Piezometer – An instrument that measures water pressure.

Precipitation - Water falling from the air: rainfall, snow, hail.

Recharge – Process of water added to the zone of saturation, either natural or artificial.

Retention - That part of the precipitation falling on a drainage area which does not escape as surface streamflow during a given period.

Salinity - The amount of salt in water. This is measured by drying water and measuring the remaining salts (Total Dissolved Solids), or by measurements of an electric current through water (conductivity).

Salt Intrusion - Phenomenon occurring when a body of salt water invades a body of fresh water. It can occur either in surface or groundwater bodies.

Seepage - Slow movement of water in a porous medium. Seepage can also refer to loss of water by infiltration into the soil from a canal or other body of water.

Sewage - Water supply from a community after it has been fouled by various uses. It may be a combination of liquid domestic, municipal and industrial waste, together with groundwater, surface water, and storm water.

Sheet flow - Flow in a relatively thin sheet, of nearly uniform thickness, over the soil surface.

Siphon - A siphon utilizes atmospheric pressure to affect or increase the flow of water it carries. It may occur naturally in karstic regions.

Stormwater - Water that is generated by rainfall and is often routed into drainage systems in order to prevent flooding.

Subsidence - Lowering in elevation of a considerable area of land surface, due to the removal of liquid or solid underlying material or removal of soluble material by means of water.

Surface water - Water which flows over or is stored on the surface of the ground

Transboundary – Across borders.

Tube well - Well made by driving a tube into the earth to a stratum that bears water.

Unconfined aquifer – An aquifer which is not confined by a restrictive layer. The top of an unconfined aquifer is the water table. (Unconfined aquifers are not pressurized).

Source: International Glossary of Hydrology, UNESCO IHP
webworld.unesco.org/water/ihp/db/glossary/glu/aglu.htm

ANNEX 2 | ORGANIZATIONS

Domestic water supply, Afghanistan

ORGANIZATIONS SUPPORTING AND IMPLEMENTING GROUNDWATER MANAGEMENT

Acacia Water

The goal of Acacia Water is to highlight the important role of groundwater in hydrological processes, as well as groundwater's importance to society. Acacia Water focuses on five themes; Groundwater and Small Islands, Groundwater and Coastal Areas, Groundwater and Climate, Groundwater and Education, Groundwater and Environment. Strategies for optimizing the use of fresh, brackish and saline water, as well river and waste water are some of those developed by the institute.

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Andhra Pradesh Farmer Managed Groundwater Systems (APFAMGS)

The APFAMGS project is located in the southern part of the Republic of India. It covers about 638 villages in seven drought-prone districts of Andhra Pradesh. The project components include: farming men and women able to understand groundwater systems, a hydrological database using the GIS platform, adoption of alternative agricultural practices suiting the availability of groundwater, community-based institutions established for alternative management of groundwater resources with equal representation/participation of men and women. The website gives a complete project overview and includes a selection of the GIS maps.

E info@apfamgs.org
I www.apfamgs.org

Arsenic Remediation Technologies: Online Informational Database

This online database contains information on all kinds of remediation technologies concerning arsenic. The homepage is a table of contents in which you can click on every technology for further information.

I web.mit.edu/murcott/www/arsenic/database.html

British Geological Survey, BGS

The British Geological Survey (BGS) is the world's longest established national geological survey and the UK's premier centre for earth science information and expertise. In the field of groundwater BGS is active in numerous projects, worth a visit on their internet site. Their research activities include Groundwater Mapping, Groundwater Pollution and Aquifer Modelling ARGOSS - Assessing risk to groundwater from on-site sanitation, COMMAN - Community Management of Groundwater Resources in Rural India, A new manual for developing groundwater for rural water supplies, Hydrogeology - Groundwater Systems & Water Quality Programme and research on groundwater and flooding in Oxford.

A BGS - Headquarters, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG, UK
T +44 (0) 115 936 3100
E www-bgs@bgs.ac.uk
I www.bgs.ac.uk

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) - The Federal Institute for Geosciences and Natural Resources is committed to sustainable use of natural resources and the protection of human habitat. Concerning groundwater, BGR advises the ministries of the German Federal Government on resource exploration, quantitative and qualitative assessment of groundwater resources and their use, groundwater protection and geothermal use of groundwater. Worldwide the BGR is active in various development and cooperation projects.

A	BGR, Geozentrum Hannover, Stilleweg 2, D-30655, Hannover, Germany
T	+49 (0) 511 643 0
E	poststelle@bgr.de
I	www.bgr.bund.de

Cap-net
Cap-net is a global capacity-building network in integrated water resource management (IWRM), providing support for regional and national networks of IWRM training, and strengthening the water curricula of educational institutions. Cap-net works with partners to train trainers, and to organize seminars to promote local awareness, competence and better understanding of IWRM. Cap-net has helped to establish and strengthen regional IWRM networks.

A	Cap-net, Corner of Frederika Street and 18th Ave. P.O. Box X03, Pretoria, South Africa
T	+27 12 3309074
E	info@cap-net.org
I	www.cap-net.org

Center for Environment and Development for the Arab Region and Europe (CEDARE)
CEDARE was established in 1992 as an international intergovernmental organization with diplomatic status. CEDARE's vision summarised reads 'environmental development' which places the environment - first and foremost - as a development issue. One of the priority areas to which CEDARE has drawn attention is water resources management, in particular concerning the transboundary Nubian aquifer.

A	CEDARE, 2 El Hegaz Street, Cairo 11737, Egypt
T	+202 451 3921/2/3/4
E	email@cedare.int
I	www.cedare.int

Drinking Water Resources
This website contains a lot of information on drinking water including a useful table on water treatment methods.

I	www.cyber-nook.com

ECOLEX
This is a database on environmental law. On the homepage you choose what kind of document you are searching for (Treaties, national legislation, court decisions or literature). On the next screen you can choose on what subject you want to get the information. "Water" is one of the subjects.

E	feedback@elc.iucn.org
I	www.ecolex.org

Eijkelkamp Agrisearch Equipment BV

Eijkelkamp Agrisearch Equipment is an international company that supplies a complete range of equipment for environmental and agricultural research. Corner stones of Eijkelkamp are sound information, products of high quality, reliable delivery and full attention to after-sales-service. Training courses are also offered which focus on practical application (theory & practice).

A Nijverheidsstraat 30, 6987 EM Giesbeek, The Netherlands
T +31 313 880200
E info@eijkelkamp.com
I www.eijkelkamp.com

Euro-Med Participatory Water Resources Scenarios (EMPOWERS)

EMPOWERS is a regional partnership of 15 organizations allied together to improve long-term access to water by local communities. EMPOWERS means to do so by advocating stakeholder-led activities to empower local people in integrated water resources management and development. EMPOWERS' outputs (also placed on the internet) include guidelines for water governance, a training manual on pro-poor participatory planning of community water services and continuous publication of working papers intended to communicate outputs which have been developed.

A EMPOWERS, Jubeiha 11941, Amman, Jordan
T + 962 6 533 2993
I www.empowers.info

Food and Agriculture Organization (FAO)

The Food and Agriculture Organization of the United Nations leads international efforts to defeat hunger. Serving both developed and developing countries, FAO acts as a neutral forum where all nations meet as equals to negotiate agreements and debate policy. FAO activities comprise four main areas; putting information within reach, sharing policy expertise, providing a meeting place for nations, bringing knowledge to the field. FAO's knowledge dissemination also occurs in the field of groundwater abstraction and agricultural water supply.

A FAO headquarters, Viale delle Terme di Caracalla, 00100 Rome, Italy
T +39 06 57051
E fao-hq@fao.org
I www.fao.org

Fluoride Action Network (FAN)

The Fluoride Action Network is an international coalition seeking to broaden public awareness about the toxicity of fluoride compounds and the health impacts of current fluoride exposures.

A Fluoride Action Network, 82 Judson St, Canton NY 13617, USA
T +1 802 338 5577
E info@fluoridealert.org
I www.fluoridealert.org

Global Agriculture Monitoring (GLAM)

GLAM uses moderate resolution satellite data to enhance the agricultural monitoring and crop forecasting capabilities of the

Foreign Agricultural Service. GLAM is a collaboration between NASA/GSFC, USDA/FAS, SSAI and UMD Department of Geography.

I www.pecad.fas.usda.gov/glam.cfm

Global Water Partnership (GWP)
The Global Water Partnership is a global network organization of several regional, national and local networks, dedicated to the promotion of IWRM. The goals of the GWP are to establish partnerships and mobilize political will, build strategic alliances for action, promote experiences in integrated water resource management, and develop and implement regional actions. GWP has eight Regional Water Partnerships and over 30 country water partnerships.

A GWP Secretariat, Drottninggatan 33, SE-111 51 Stockholm, Sweden
T +46 (0)8 562 51 900
E gwp@gwpforum.org
I www.gwpforum.org

Groundwater Central
The Groundwater Central is a search engine based on groundwater information available on the internet. The aim of the Groundwater Central is to improve the efficiency of internet research for the interested public. The database crosscuts and centralizes information found at a variety of web sites.

I www.groundwatercentral.info

The Groundwater Foundation
The foundation's mission statement is educating and motivating people to care for and about groundwater. Founded on the principle that education is a powerful motivator, the groundwater foundation offers a range of educational material for pupils and educators and is involved in educational events and programmes. The kids' corner offers amongst others online games, groundwater basics and educational 'try this at home' experiments.

A The Groundwater Foundation, 5561 S. 48th St., Ste. 215, Lincoln, NE 68516, USA
T +1 402 434 2740
E info@groundwater.org
I www.groundwater.org

Groundwater Governance in Asia, IWMI-GGA
The project: 'Groundwater Governance in Asia – Capacity Building through Action Research in the Indo-Gangetic and Yellow River Basins', or in short the GGA-project, sets out to address the pertinent and very pressing issues of groundwater. The regions covered by the project are; the basin states of the Indo-Gangetic (IGB) and Yellow River (YRB) Basins, i.e. Pakistan, India, Nepal, Bangladesh,and China.

A IWMI-GGA, NASC Complex, Dev Prakash Shastri Marg, Pusa, New Delhi 110 012, India
T +91 11 2584 0811/12
I www.waterandfood.org/gga

Groundwater Management
Training kits, exercises and reference materials concerning participatory groundwater management are part of the new internet site on groundwater management. Intended to bring together scattered experience on groundwater management and its aspects the site managers welcome collaboration as well as relevant material. Free of charge all materials are offered online or are available on CD-ROM from MetaMeta, based in the Netherlands.

A MetaMeta, Paardskerkhofweg 14, 5223 AJ 's-Hertogenbosch, The Netherlands
T +31 (0) 73 5230848
E info@metameta.nl
I www.groundwatermanagement.org

International Association of Hydrogeologists (IAH)
IAH is a scientific and educational organization whose aims are to promote research into and understanding of the proper management and protection of groundwater for the common good throughout the world. IAH's website contains information on groundwater and groundwater events and IAH's activities. IAH works with various organizations on promoting groundwater awareness.

A IAH Secretariat, P.O. Box 4130, Goring, Reading, RG8 6BJ, UK
T +44 870 762 4462
E info@iah.org
I www.iah.org

Groundwater Management Advisory Team (GW•MATE)
GW•MATE is a core group of experienced specialists in the multidisciplinary and multifaceted subject of groundwater management. They will act globally over a period of about five years to develop operational capacity and capability in groundwater resource management and quality protection. The strategy is to use World Bank project activities, together with the Global Water Partnership (GWP) regional networks, as the points of entry to achieve this goal.

I www.worldbank.org/gwmate

GrundWasser-online
GrundWasser-Online is a German information portal on groundwater which also functions as a cooperative network. A variety of sources is represented on the website (links, maps, project descriptions etc.).

I www.grundwasser-online.de

India Water Portal
This water portal is an open web-based platform for sharing information on water management amongst water practitioners. Courses on groundwater are freely available.

I www.indiawaterportal.org

International Atomic Energy Agency (IAEA)
The IAEA is the lead UN agency in isotope and related nuclear techniques and provides the basic means of using these

techniques in the form of global reference data and isotope reference materials. The tasks of the water resources programme of the IAEA are amongst others: exchange of information, training and cooperation with international organizations in isotope hydrology, isotope methods for the assessment of groundwater sustainability, development of isotope methodologies for water quality assessment and management and development of Member State capacity for isotope analysis of hydrological samples.

A International Atomic Energy Agency, Wagramer Strasse 5, A-1400 Vienna, Austria
T +43 1 2600-0
E official.mail@iaea.org
I www.iaea.org

International Development Research Centre (IDRC)
IDRC is a Canadian Crown corporation that works in close collaboration with researchers from the developing world in their search for the means to build healthier, more equitable, and more prosperous societies. Concerning groundwater and water supply IDRC has focused on water supply technologies, such as improved water pumps and rooftop water collection systems. Now, the focus lies on water treatment and quality control, water demand management and the devolution of water management to lower levels of government, local organizations and communities. The development of simple water testing kits, which can be used by local people to examine the quality of water, is one example.

A IDRC, Ottawa, 250 Albert Street, Ottawa, ON, Canada.
T +1 613 236 6163
E info@idrc.ca
I www.idrc.ca

International Groundwater Resources Assessment Centre (IGRAC)
IGRAC is an initiative of UNESCO and WMO and was launched at the "Fifth International Conference on Hydrology" in February 1999. The Centre aims at facilitating and promoting world-wide exchange of groundwater knowledge to encourage and enhance the conjunctive and sustainable use of both groundwater and surface water. IGRAC has developed a global groundwater information system (GGIS). The system acts as an interactive and transparent portal to groundwater-related information and knowledge which is simple to use and publicly available through the internet.

A IGRAC, Princetonlaan 6, Utrecht, 3508 TA, The Netherlands
T +31 (0) 30 2564270
E info@igrac.nl
I igrac.nitg.tno.nl

International Mine Water Association (IMWA)
This association has the objective to protect the environment against the impact of mine drainage and related activities. It was founded in 1979 in Spain. Since then the association has organized a congress every three years. Membership of IMWA is open to everyone with an interest in mine water.

I www.imwa.info

International Union for the Conservation of Nature (IUCN)
IUCN brings together states, government agencies and a diverse range of NGOs in a world partnership, with over 1000 members from 140 countries. IUCN's mission is to influence, encourage and

assist societies throughout the world to conserve the integrity and diversity of nature and to ensure that any use of natural resources is equitable and ecologically sustainable. One of its main themes is 'water and wetlands' which encompasses several projects all over the world in which groundwater also plays a topical role. The involvement of local community groups is always an important part of the projects.

A IUCN, Rue Mauverney 28, Gland 1196, Switzerland
T +41 22 999 0000
E webmaster@iucn.org
I www.iucn.org

International Water and Sanitation Centre (IRC)
IRC aims to facilitate the sharing, promotion and use of knowledge so that governments, professionals and organizations can better support poor men, women and children in developing countries to obtain water and sanitation services they will use and maintain. Amongst others, the IRC is involved in projects concerning groundwater quality and sufficient safe domestic water sources.

A IRC, Westvest 7, 2611 AX, Delft, The Netherlands
T +31 (0) 15 2192939
I www.irc.nl

International Water Law Project (IWLP)
The mission of the International Water Law Project (IWLP) is to serve as the premier resource on the internet for international water law and policy issues. Its purpose is to educate and provide relevant resources to the public and to facilitate cooperation over the world's freshwater resources. IWLP will continue to update its pages and databases and welcomes and appreciates contributions and submissions including new publications, URLs, news stories, cases, corrections and comments.

I www.waterlaw.org

Internationally Shared Aquifer Resources Management (ISARM)
The global ISARM (Internationally Shared Aquifer Resources Management) initiative is a UNESCO-led multi-agency effort aimed at improving the understanding of scientific, socio-economic, legal, institutional and environmental issues related to the management of transboundary aquifers.

A ISARM Secretariat, 1 Rue Miollis 75732, Paris Cedex 15, France
T +33 (01) 4568 3995
E ihp@unesco.org
I www.isarm.net

Irrigation and Water Engineering Group, Wageningen University (IWE)
IWE is committed to understanding all there is to water in agriculture. It distinguishes three major fields of interest in its research and teaching: Irrigation Technology and Agro-Ecology (Sustainability), Irrigation Policy and Politics (Democracy), Water Rights, Irrigation and Livelihoods (Equity), and focuses on the different levels of interaction (farm to watershed level) from a socio-technical perspective. IWE teaches both BSc and MSc courses as part of the study programme International Land and Water Management.

A Irrigation and Water Engineering Group, Wageningen University, Droevendaalsesteeg 3a, 6708 PB Wageningen, The Netherlands
T +31 (0) 317 484190
E gerda.defauw@wur.nl
I www.iwe.wur.nl

IWMI – TATA Water Policy Program
The IWMI-Tata Water Policy Research Program was established under a financial partnership between IWMI and Sir Ratan Tata Trust, Mumbai with the idea of promoting practical, policy research in water resources management. The Program has been in operation since March 2000; and since then, it has worked with some 40 partners and completed over 70, usually small, research projects. Various projects include groundwater and management thereof and water harvesting in India.

I www.iwmi.cgiar.org/iwmi-tata_html

KM4dev
This abbreviation stands for Knowledge Management for development. The website is a community of international development practitioners. On the site is a search function you can use to find articles, books, links or persons. If you register you can add information to the page or participate in online forums.

E km@bellanet.org
I www.km4dev.org

La Mesilla Ditch Association
La Mesilla Ditch Association is a membership organization in New Mexico, USA where an irrigation system with acequias is used. The objective of the La Mesilla Acequia association website is to provide information about the history of the membership, water rights and responsibilities each member has.

E LMAcequia@lanl.gov
I www.lmacequia.org

Managing Connected Water Resources
The collaborative project 'Managing Connected Water Resources' between three governmental organizations in Australia aims for a more coordinated approach in the management of surface water and groundwater resources. The project components consist of; trial catchments to test methodologies and approaches, a National Workshop on managing connected water resources and the 'Connected Water' website. The latter offers guidance for water managers, catchment groups and policy makers in assessing and managing the key information gap of how surface water features like rivers, lakes and wetlands interact with aquifers, and how this interaction can affect water quantity and quality.

I www.connectedwater.gov.au

Nalgonda
The Nalgonda district in India suffers from strongly contaminated groundwater by fluoride. The Nalgonda website provides information on fluoride contamination, current status and projects.

E info@nalgonda.org
I www.nalgonda.org

National Sanitation Foundation (NSF)
NSF is an independent non-profit organization. NSF writes standards for food, water, air and consumer goods. Their aim is to encourage everyone to live safely. On their internet site a lot of information on water treatment systems can be found.

E info@nsf.org
I www.nsf.org

The Nature Conservancy (TNC)
The Nature Conservancy is an organization working around the world to protect ecologically important lands and water for nature and people. The Nature Conservancy developed Indicators of Hydrologic Alteration (IHA). This is a software programme for those trying to understand the hydrological impacts of human activities or trying to develop environmental flow recommendations for water managers.

A Worldwide Office, The Nature Conservancy, 4245 North Fairfax Drive, Suite 100, Arlington, VA 22203-1606, USA
T +1 (703) 841-5300
I www.nature.org

Netherlands Water Partnership (NWP)
The NWP is an independent body set up by the Dutch private and public sectors. They nationally coordinate water activities overseas and provide relevant information regarding these activities.

The main goals of the NWP are to harmonize the activities and initiatives of the Dutch water sector overseas and promote Dutch water expertise worldwide. The organization acts as focal point in the exchange of information among the more than 130 Dutch members.

A NWP, Westvest 7, 2611 AX Delft, The Netherlands
T +31 (0)15 2151728
E info@nwp.nl
I www.nwp.nl

Practica Foundation
The mission of the Practica Foundation is poverty alleviation through dissemination of best practices and development and promotion of appropriate water and energy-related technologies and services. With products such as innovative low-cost drilling methods, wells and pumps the foundation aims at delivering smart water technologies which have proven to be sound and sustainable alternatives in many different situations.

A Practica Foundation, Schoorweg 22, 3356 BK, Papendrecht, The Netherlands
T +31 (0)78 6410222
E info@practicafoundation.nl
I www.practicafoundation.nl

Project WET – Water education for teachers
The mission of Project WET is to reach children, parents, educators, and communities of the world with water education. The global Project WET network is comprised of individuals who care about reaching children with information and educational materials

on water resources, its management and protection. Project WET offers a wide range of educational material also specifically concerning groundwater awareness and conservation.

A Project WET, 1001 West Oak, Suite 210, Bozeman, MT 59715, USA
T +1 406 585 2236
E info@projectwet.org
I www.projectwet.org

Rainwaterharvesting.org
With an extensive overview of the water harvesting techniques from the Indian sub-continent this internet site serves as a primary reference for its topic. Illustrations and descriptions of the technology as well as research tools and networking possibilities are - amongst others - offered on the internet site.

I www.rainwaterharvesting.org

Ramsar Convention on Wetlands
The Convention on Wetlands is an intergovernmental treaty which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. It was adopted in the Iranian city of Ramsar in 1971 and came into force in 1975, and it is the only global environmental treaty that deals with a particular ecosystem. The Convention's member countries cover all geographic regions of the planet. The handbook for wise use of wetlands and related sources that was created comprises a set of nine handbooks containing guidelines, supporting background documents, photographs, case studies and cross-references.

A Ramsar Convention Secretariat, Rue Mauverney 28, CH-1196, Gland, Switzerland
T +41 22 999 0170
E ramsar@ramsar.org
I www.ramsar.org

RiPPLE Ethiopia
The Research-inspired Policy and Practice Learning in Ethiopia and the Nile Region (RiPPLE) is a five-year research programme consortium which focuses on evidence-based learning on water supply and sanitation. On their website you will find papers, pictures, newsletters etc.

A RiPPLE Office, P.O.Box 4812, Addis Ababa, Ethiopia
T +251 114 160075
E info@rippleethiopia.org
I www.rippleethiopia.org

Rural Water Supply Network (RWSN)
RWSN is a global knowledge network and promotes sound practices in rural water supply. They specifically focus on improvement in the application of groundwater technologies for rural communities. RWSN wants to strengthen the sustainability, efficiency and effectiveness of rural water supply services. Documentation and links can be found on their website.

A RWSN Secretariat, Skat Foundation, Vadianstrasse 42, CH-9000 St. Gallen, Switzerland
T +41 712 285 454
E rwsn@skat.ch
I www.rwsn.ch

Scorecard
This is a pollution information site on all kind of pollutions, including groundwater contamination in the USA. Besides information on places where pollution occurs, other information like who is polluting can be found.

E scorecard@getactive.com
I www.scorecard.org

SOS Arsenic Poisoning in Bangladesh
Website providing information on arsenic-polluted water in Bangladesh. Project reports, news items, maps and pictures are available on the site.

I www.sos-arsenic.net

South African Groundwater Division Western Cape (GWDWC)
The Groundwater Division wants to promote groundwater and increase technical information sharing amongst hydrogeologists and other non-specialists. Rain graphs can be found and lists of interesting links and articles are available.

T (+27) 218 801 079
E julian@geoss.co.za
I www.gwdwc.co.za

South Pacific Applied Geoscience Commission (SOPAC)
SOPAC is an inter-governmental, regional organization dedicated to providing products and services in three technical programme areas of: Community Lifelines; Community Risk; and Ocean and Islands. Under the community lifeline programme on SOPAC's internet site its members are offered an array of information on water demand management, water quality, waste water and water governance. The Pacific Resource Centre on Water and Climate is also hosted on the site in which projects, research and topical issues are further explained.

I www.sopac.org

Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA)
SAHRA's mission is to identify critical stakeholder-relevant knowledge gaps and conduct basin-focused multidisciplinary research to fill them; and to convey what is known and what is being learned to improve water management and policy. SAHRA aims for a lasting legacy in the field of integrated semi-arid hydrology. The legacy includes the fields of; Science, Stakeholders, Knowledge Transfer, Education and Institutions.

A SAHRA (5th Floor), 845 N. Park, Tucson, AZ 85721-0158, USA
T +1 520 626 6974
I www.sahra.arizona.edu

UK Groundwater Forum
The aim of the UK Groundwater forum is to raise awareness of groundwater and the role it plays in supporting the environment and in water supply. The Forum prepared an excellent video on the interaction between surface and groundwater.

A UK Groundwater Forum Secretariat, Maclean Building, Wallingford, Oxfordshire OX10 8BB, UK
E contact@groundwateruk.org
I www.groundwateruk.org

UNESCO - International Glossary of Hydrology
Authored by the French IHP National Committee, UNESCO offers an International Glossary of Hydrology (IHP, International Hydrological Programme). The glossary is available in 11 languages, offers a comprehensive list of hydrological terms and the possibility to translate them into various languages.

I www.cig.ensmp.fr/~hubert/glu/aglo.htm

UNESCO – International Hydrological Programme (IHP)
IHP is UNESCO's international scientific cooperative programme in water research, water resources management, education and capacity building, and the only broadly-based science programme of the UN system in this area. Member states, professional and scientific organizations can: upgrade their knowledge of the water cycle, develop techniques, methodologies and approaches to better define hydrological phenomena and improve water management, locally and globally. IHP further acts as: a catalyst to stimulate cooperation and dialogue in water science and management, to assess the sustainable development of vulnerable water resources, and serves as a platform for increasing awareness of global water issues. The internet site also offers a complete overview and links to Institutes and Centres under the auspices of UNESCO.

I http://typo38.unesco.org/index.php?id=240

UNESCO – World Water Assessment Programme (WWAP)
This UN-wide programme seeks to develop the tools and skills needed to achieve a better understanding of those basic processes, management practices and policies that will help improve the supply and quality of global freshwater resources. Its goals are to: assess the state of the world's freshwater resources and ecosystems; identify critical issues and problems; develop indicators and measure progress towards achieving sustainable use of water resources; help countries develop their own assessment capacity; document lessons learned and publish a World Water Development Report (WWDR) at regular intervals.

I www.unesco.org/water/wwap/index.shtml

United Nations Children's Fund (UNICEF)
Founded by the United Nations in 1946 to bring relief to war-affected children, supporting equally those in vanquished as well as victorious countries UNICEF has various programmes related to water and groundwater protection in view of a safer domestic source.

A UNICEF Headquarters, 3 United Nations Plaza, New York, New York 10017, USA
T +1 212 326 7000

I www.unicef.org

United Nations Environment Programme (UNEP)
In the field of water resources, UNEP facilitates and catalyses water resource assessments in various developing countries, implements projects that assist countries in developing integrated water resource management plans, creates awareness of innovative alternative technologies and helps to develop, implement and enforce water resource management policies, laws and regulations. UNEP's water unit is responsible for the assessment of the world's water resources where it carries out comprehensive assessments of the world's fresh water including an assessment of groundwater vulnerability.

A UNEP, United Nations Avenue, Gigiri 00100, Nairobi, Kenya
T +254 20 7621234
E unepinfo@unep.org
I www.unep.org

Unites States Environmental Protection Agency (U.S. EPA)
The EPA of the United States wants to protect human health and environment. Their standards (for example maximum amount of arsenic in drinking water) are widely used. On the website a lot of information can be found on groundwater. There is also a place reserved for children and teachers and they even set up hotlines on numerous topics, for example on safe drinking water.

A EPA-Headquarters, Ariel Rios Building, 1200 Pennsylvania Avenue, N.W., Washington, DC 20460, USA
T +1 202 272 0167
I www.epa.gov

USFilter
USFilter is part of the Siemens family of companies. They deliver water technologies on a global scale. On this website products can be found easily by a structured drill down menu.

I www.usfilter.com

WaterAid
WaterAid is an international charity. Their mission is to overcome poverty by enabling the world's poorest people to gain access to safe water, sanitation and hygiene education. WaterAid and its partners work with individuals and families in their communities and use a mixture of low-cost technologies to deliver lasting water, sanitation and hygiene solutions.
A 47-49 Durham Street, London SE11 5JD, UK
T +44 (0)20 7793 4500
I www.wateraid.org

Water Education Foundation
The Foundation's mission is to create a better understanding of water issues and help resolve water resource problems through educational programmes. The Water Education Foundation is an extensive and useful resource for information about water resource issues and educational matters.

A Water Education Foundation, 717 K Street, Suite 317, Sacramento, CA 95814, USA
T +1 916 444 6240
I www.water-ed.org

Water Environment Partnership in Asia (WEPA)
WEPA, in cooperation with 11 countries in East Asia, aims to promote good governance in water environment management by providing necessary, relevant information and knowledge, through a series of databases. It further aims to develop the capacity of relevant stakeholders by working together on the construction of the databases. The databases comprise; policy-related information, technologies for water environment conservation, information related to activities by NGOs and CBOs, and a database on information sources.

A WEPA secretariat at IGES headquarters, 2108-11 Kamiyamaguchi, Hayama, Kanagawa, Japan
T +81 46 855 3743
E contact@wepa-db.net
I www.wepa-db.net

Water for Arid land
This useful website contains a number of practical manuals on water harvesting.

I www.waterforaridland.com

Water Framework Directive Visualisation Package (WFDVisual)
The WFDVisual site contains images of some of the complex processes underpinning the water environment and its management under the Water Framework Directive (WFD). The website principally focuses on different concepts relating to groundwater and its management. The website hosts over 1000 images; covering many topographic and land-use settings and depicting concepts such as pathway characteristics (e.g. aquifer type, vulnerability), pressures on groundwater and receptor type (e.g. river, wetland, borehole). The user is able to apply different scenarios in order to select a package of images relevant to their own individual requirements.

I www.wfdvisual.com

Water Science for Schools
This U.S. Geological Survey websit provides information on a variety of aspects of water. The language on the site makes it accessible to children.

I ga.water.usgs.gov/edu

WaterNet
WaterNet is a network in the Southern African region (SADC) of 52 university departments and research and training institutes specializing in water. The network aims to build regional institutional and human capacity in Integrated Water Resources Management (IWRM) through training, education, research and outreach by harnessing the complementary strengths of member institutions in the region and elsewhere.

I www.waternetonline.org

WaterWatch
WaterWatch is a scientific advisory firm, active in the niche of remote sensing and water resources management. Satellite image analysis to support water management applications is their core activity. The portfolio covers essentially irrigation and drainage

studies throughout the world, but also environmental studies on the allocation of ecological water demands in river basins. WaterWatch has developed a groundwater planning tool, called GroundBuck that positions groundwater use as part of the overall waterbalance for a basin.

A WaterWatch, Generaal Foulkesweg 28A, Wageningen, 6703 BS, The Netherlands
T +31 (0) 317 423401
E info@waterwatch.nl
I www.waterwatch.nl

World Health Organization (WHO)
WHO is the directing and coordinating authority for health within the United Nations system. WHO works amongst others on aspects of water, sanitation and hygiene where the health burden is high, where interventions could make a major difference and where the present state of knowledge is poor. The programmes and projects of the WHO include; Drinking-water quality, Water resources, Water supply and sanitation monitoring, and Wastewater use.

A WHO, Avenue Appia 20, 1211 Geneva 27, Switzerland
T +41 22 791 2111
E info@who.int
I www.who.int

World Water Council (WWC)
The World Water Council is an international water policy think-tank dedicated to strengthening the movement for improved management of the world's water resources. The WWC's mission is to promote awareness and build political commitment on critical water issues at all levels. To fulfil its missions and objectives, the Council has created the World Water Forum, the largest international event in the field of water, organized every three years in close collaboration with the authorities of the hosting country. A list of members can be found on the WWC website.

A WWC Headquarters, Espace Gaymard, 2-4 place d'Arvieux, 13002 Marseille, France
T +33 491 99 41 00
E wwc@worldwatercouncil.org
I www.worldwatercouncil.org

World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP)
In order to contribute to the world-wide efforts to better study, manage and protect freshwater resources, WHYMAP was launched in 1999. The programme aims to collect, collate and depict hydrogeological information at a global scale.

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ANNEX 3| SOURCES

Collecting water from a well in Ban Nam Lai, Laos

Pictures on cover: MetaMeta
Picture on title page: MetaMeta

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PICTURES ANNEXES AND BACK COVER

Annex I	Soil and Manure in Senegal: MetaMeta
Annex II	Irrigating in Iran: MetaMeta
Annex III	Collecting water in Laos: MetaMeta
Back cover	Using mirror in Pakistan: MetaMeta

Groundwater Withdrawals: Annual per capita Units in cubic metres (m^3) per person

Country	Groundwater withdrawal (m^3/person) 1973 - 2005	Country	Groundwater withdrawal (m^3/person) 1973 - 2005	Country	Groundwater withdrawal (m^3/person) 1973 -2005	Country	Groundwater withdrawal (m^3/person) 1973 - 2005
Albania	184.5	Gabon	0.0	Madagascar	1.5	Slovakia	111.9
Algeria	118.8	Georgia	549.5	Malaysia	19.6	Slovenia	101.1
Argentina	180.4	Germany	89.4	Maldives	0.0	Somalia	1.1
Australia	140.7	Ghana	5.5	Mali	11.3	South Africa	61.8
Austria	174.0	Greece	196.9	Malta	77.9	Spain	135.2
Bangladesh	97.8	Guinea	13.9	Mauritania	496.7	Sudan	13.3
Belarus	117.3	Guinea-Bissau	22.7	Mauritius	119.0	Sweden	68.0
Belgium	81.1	Hungary	97.9	Mexico	275.4	Switzerland	126.4
Benin	6.6	Iceland	749.1	Mongolia	171.2	Syrian Arab Rep	130.0
Botswana	74.8	India	224.5	Morocco	108.8	Tajikistan	405.9
Brazil	56.7	Iran, Islamic Rep	737.1	Namibia	69.7	Thailand	15.1
Brunei Darussalam	138.9	Iraq	13.1	Netherlands	73.6	Tunisia	199.6
Bulgaria	565.5	Ireland	55.4	Niger	13.9	Turkey	120.5
Canada	36.1	Israel	218.0	Norway	96.3	Turkmenistan	97.4
Chad	17.2	Italy	244.2	Oman	262.0	Ukraine	77.3
China	47.1	Japan	108.4	Pakistan	527.3	United Arab Emirates	640.8
Congo	7.0	Jordan	130.2	Peru	139.4	United Kingdom	43.3
Cuba	408.3	Kazakhstan	142.9	Philippines	83.2	United States	429.4
Cyprus	129.9	Korea, Rep	55.5	Poland	51.8	Uzbekistan	331.2
Czech Rep	48.4	Kuwait	172.6	Portugal	312.6	Viet Nam	12.1
Denmark	172.2	Kyrgyzstan	132.7	Qatar	389.9	Yemen	142.4
Djibouti	27.0	Lebanon	144.1	Romania	157.0	Zambia	8.2
Egypt	103.9	Libyan Arab Jamahiriya	815.0	Saudi Arabia	869.9	Zimbabwe	33.2
Finland	39.2	Lithuania	56.1	Senegal	47.1		
France	103.7	Luxembourg	74.1	Seychelles	3.7		

Source: World Resource Institute, EarthTrends. www.earthtrends.wri.org.