Groundwater under Threat

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Editors: Birgitta Johansson and Björn Sellberg, Formas

Translation: Lewis Gruber

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Groundwater – a precious resource

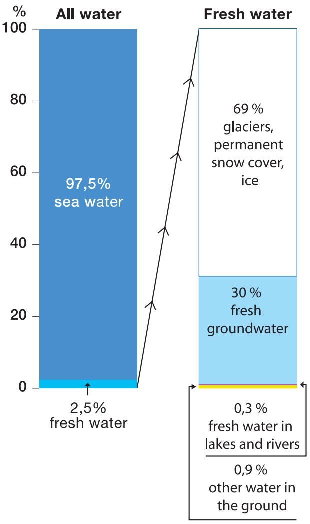
The more the earth's population grows, the greater is the pressure on water resources. In many areas, surface water of sufficiently good quality for use as drinking water is no longer available in sufficient quantities. In these places, people are increasingly dependent on groundwater. But what happens when groundwater is also threatened by contamination and scarcity?

Lisa Sennerby Forsse
Secretary General
Formas

The availability of fresh water will be one of the most serious resource and environmental issues for a long time to come. So far we have mostly discussed surface water. But surface water is only a very small part of fresh water on earth. Almost all fresh water in liquid form is stored in groundwater reservoirs. It is now found that this hidden and valuable resource is also threatened by contamination and over traction. When we most need it, it might be too late. We must therefore quickly learn how it can best be managed.

About one third of the people on earth are almost completely dependent on groundwater for their drinking water supplies. This is the situation for people in several megacities in the third world, and the same also applies to most of the rural population in India. A large proportion of the most fertile agricultural land on earth is irrigated with groundwater. Irrigation accounts for about two thirds of the total water consumption in the world. Rivers and lakes dry out or become contaminated, and the need for food increases. The demand for groundwater for irrigation increases at the same rate. In some areas the situation is so bad that fossil groundwater, which cannot be renewed, is used.

Water dissolves many contaminants which are then transported down into the groundwater. It takes longer for groundwater than surface water to be contaminated. But once groundwater has become contaminated, it is very difficult and expensive to make it clean again. In practice, groundwater contamination is more or less permanent, since the turnover rate is extremely slow. Fertilisers and pesticides, seepage from industries, waste



Only a few per cent of water on earth is fresh water. Most of this is frozen water. Almost all of the approximately 30 per cent fresh water in liquid form is stored in groundwater reservoirs.

deposits and defective sewage treatment plants are examples of the sources of contamination which may be disastrous for the quality of groundwater. Salinisation is another problem. Groundwater is no longer fit to drink in many parts of the world.

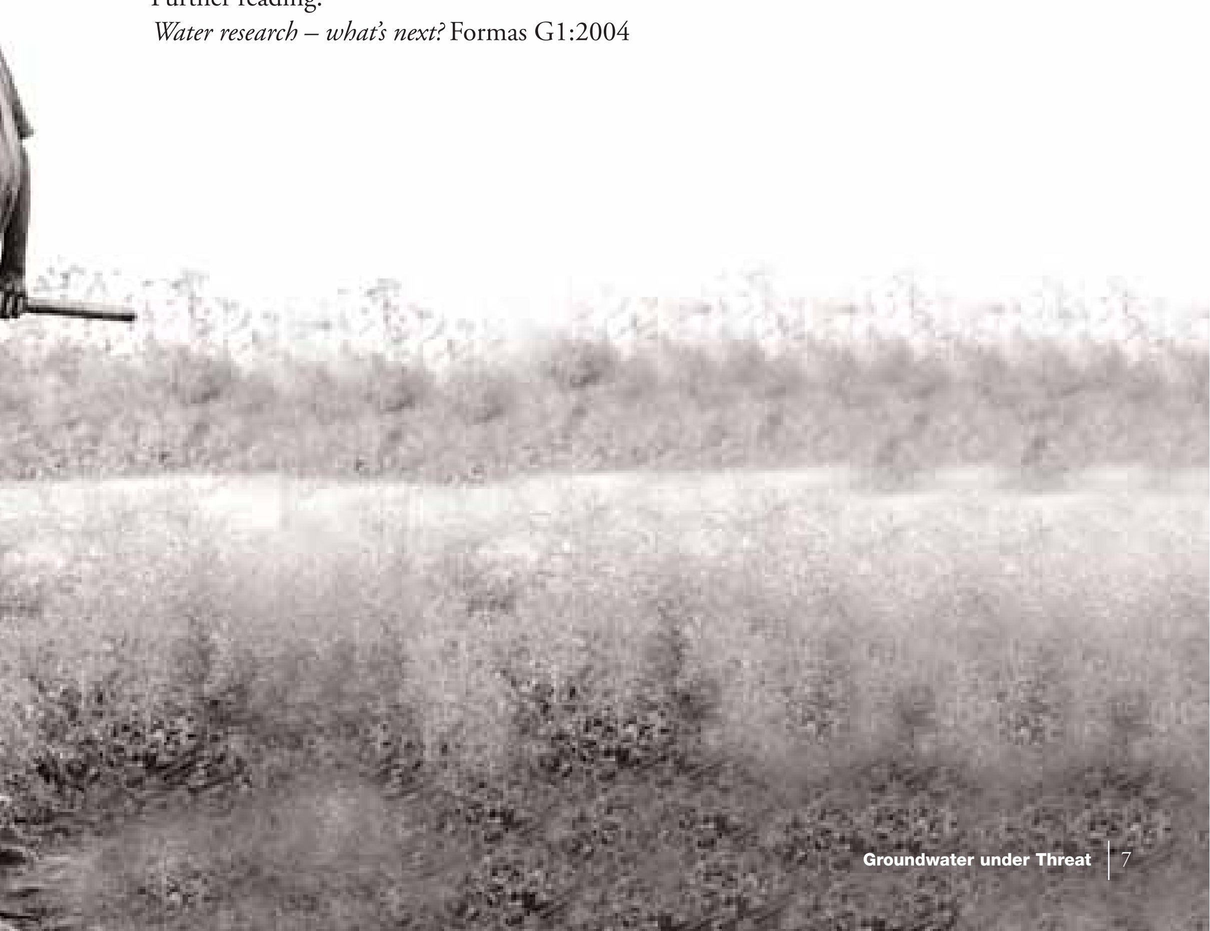
For the second year running, the Swedish Research Council Formas is publishing a booklet on water. This time it deals with groundwater from the perspective of the southern hemisphere. We have cooperated with a number of Swedish researchers who have been engaged on this problem in both theory and practice. The booklet describes different problem areas associated with groundwater, and gives examples from different parts of the world.

The UN General Assembly has declared the period 2005-2015 the 'Water for Life' decade. In the Millennium Development Goals, the countries of the world have undertaken to halve, in ten years, the number of people who do not have access to clean drinking water and acceptable sanitation. The big question is how this is to be done in an economically, socially and environmentally sustainable way. Tap and toilet are important tools in reducing disease and death. Another prerequisite is that we learn to better understand the behaviour of the groundwater basin as part of an integrated water resources management. We must also learn to plan for water use and water protection.

Research continues to have an important role in the efforts to create societies where the use of water is based on sustainable and environmental use of resources. It is not only research on how groundwater behaves and what processes affect its quality and quantity that is needed, but also research on planning and infrastructure as a whole, the way future towns and cities develop, and the way people's behaviour and life patterns influence ecosystems and social systems. The great environmental threats, such as climate change, demand powerful joint endeavours and the development of research cooperation among countries. Environmental work in an increasingly globalised world also demands knowledge of how democracy, welfare and human rights can be safeguarded. Sweden should contribute to the global pool of knowledge by developing new and vital knowledge in important areas, of which water research is one! This is one way of being a resource-strong partner in the research cooperation with countries in the southern hemisphere.

Lisa Sennerby-Forsse
Secretary General, Formas

Further reading:
Water research – what's next? Formas G1:2004



Water, equity and health

Professor Lars Åke Persson, International Maternal and Child Health, Uppsala University.

UN General Assembly has declared 2005–2015 the water decade. Therefore the momentum is strong for actions for safe water and sanitation. The countries of the world have committed themselves in the Millennium Development Goals to eradicate poverty. Tap and toilet are important tools in reducing death and disease, bridging over disparities and achieving development.

Ahmed in Bangladesh has a history of repeated episodes of diarrhoea that is interwoven with the development of malnutrition. He is constantly exposed to pathogens that cause repeated episodes of water-related diseases. Photo: Lars-Åke Persson

Ahmed, 9 months, is admitted to Matlab hospital 50 km South of Dhaka, Bangladesh, with diarrhoea and broncho-pneumonia. He suffers from one of the more than 2,000 million annual episodes of diarrhoea in the world, and he is at risk of becoming one of the 2 million deaths in diarrhoea that happen each year; most of these in young children living in middle- and low-income countries. His drinking water is not safe, and the household sanitation and hygiene are unsatisfactory. Ahmed lives in the flooded delta region in Bangladesh, an environment with contaminated surface water and unsatisfactory household hygiene and sanitation. Luckily he has parents who understood the need for prompt treatment, and he was taken to hospital where fluid therapy and additional treatment was offered. This short story summarises some of the issues regarding disparities in access to water and sanitation and the relation to public health.

Millennium Development Goals with a water target

There has been a gradual development of conventions and declarations stating that safe water and adequate sanitation should be considered human rights. This perspective on water as a human right is important for poverty alleviation and development work; it should not be seen as a commodity that may be implemented when resources allow, in due time. Rather, it is a human right for all irrespective of geography, social and religious groups, socio-economic resources, gender and age.

In 2000, 189 UN member states adopted Millennium Development Goals (MDGs) that set clear and time-bound targets to eradicate poverty. Economic factors, fundamental health problems and environmental conditions are in focus. The 7th Millennium Development Goal, Ensure Environmental Sustainability, includes an important water and sanitation target: "Halve, by 2015, the proportion of people without sustainable access to safe drinking water and sanitation". This target is monitored by UNICEF and the World Health Organization by assessing the proportion of population with sustainable access to an improved water source, divided into urban and rural areas, and the proportion of population with access to improved sanitation in urban and rural areas.

Tap and toilet are important tools

Eight out of ten of the world's population have improved drinking water sources, but still more than one billion people are not covered. Especially Sub-Saharan Africa lags behind in this development, according to a survey made by UNICEF and WHO. Half the developing world or 2,600 million people lack improved sanitation; in South Asia and Sub-Saharan Africa about a third use improved sanitation. This means that some of the potential positive health effects of safe water sources are counteracted by inadequate sanitation that keeps the occurrence of diarrhoeal diseases and other morbidity on a high level.

If the current trends persist the safe water and improved sanitation targets will not be met by 2015. Behind these general trends and geographical comparisons there are even other striking inequities. Most of the burden of unsafe water and unmet sanitation targets lies on women, who have to use considerable time on fetching water, and managing unhygienic conditions and their consequences. Further, those most exposed to this deprivation are found among the poor, and in rural communities.

Development of the human right to water

1946 The right to health (Constitution of the world Heath Organization).

1948 A right to a standard of living adequate for health and well-being (The Universal Declaration of Human Rights).

1989 Children are entitled to the enjoyment of the highest attainable standard of health; measures to combat disease and malnutrition include provision of clean drinking water (Convention of the Rights of the child).

2000 The right to health includes factors that determine good health, e.g. safe drinking water, adequate sanitation, sufficient supply of safe food, nutrition and housing, healthy occupational and environmental conditions, and access to health-related education and information (United Nations Committee on Economic, Social an Cultural Rights).

2002 Water itself is an independent human right (United Nations Committee on Economic, Social and Cultural Rights).

Burden of water related diseases

It is estimated that 90% of episodes of diarrhoea in low-income countries are attributable to unsafe water, sanitation and hygiene. Almost 2 million out of the 10 million annual child deaths under the age of five are caused by diarrhoea. Malnutrition contributes to more than half of these diarrhoea deaths. Water, salt and sugar – the oral rehydration solution that was developed in Bangladesh – have to date saved more than 40 million lives from diarrhoea deaths, but primary prevention by safe drinking water, adequate sanitation and access to rehydration therapy when needed could prevent a large proportion of these 2 million deaths.

Lack of safe water and sanitation are not only related to diarrhoeal diseases. A series of diseases and health problems may be caused by lack of water, pathogens in water, chemical contamination of water, mosquitoes breeding in water or inadequate sanitation. The total burden of diseases related to water and sanitation, including both disability and death, is not known, due to lack of reliable data, but it is estimated that diarrhoea episodes alone, caused by unsafe water and sanitation, contribute 4% of the total global burden of diseases (calculated as Disability Adjusted Life Years or DALYs). This is almost on the same level as the burden of diseases caused by smoking. The following water and sanitation related diseases are selected and based on information from the World Health Organization: Arsenicosis, Ascariasis, Campylobacteriosis, Cholera, Dengue and Dengue Haemorrhagic Fever, Diarrhoea, Fluorosis, Guinea-Worm Disease, Hepatitis, Japanese Encephalitis, Lead Poisoning, Leptospirosis, Malaria, Malnutrition, Methaemoglobinemia, Onchocerciasis, Ringworm, Scabies, Schistosomiasis, Trachoma, Typhoid and Paratyphoid Enteric Fevers.

Three prerequisites for disease prevention

The combination of safe drinking water, sanitation facilities and good personal hygiene are prerequisites for disease prevention and the fight against poverty.

Safe drinking water is not sufficient to prevent diarrhoea in a situation of unmet sanitation and hygienic needs. The extensive drilling of tube wells for drinking water in Bangladesh did not reduce the incidence of diarrhoea when poverty-driven poor sanitation and unsatisfactory personal hygiene prevailed. Well designed safe water interventions in Africa did not result in less disease when there were no improvements in sanitation and household hygiene.

The ground on which children like Ahmed will crawl is highly contaminated, the family food to which he is weaned is also frequently kept unprotected, and the hands that feed him have usually not been washed with soap and water prior to meals. The combination of safe drinking water, sanitation facilities and good personal hygiene are prerequisites for disease prevention and the fight against poverty.

Arsenic-free water now!

The Bangladesh example also illustrates the necessity of assessing water quality and complying with the international norms for drinking water quality when large-scale water programmes and interventions are performed. Since the 1970s the population has shifted from surface water as the main drinking water source to tube well water that was considered safe. It was not until the detection of arsenic contamination of tube well water in West Bengal and Bangladesh in 1993 that a process of water quality assessment and arsenic mitigation began. This arsenic contamination occurs naturally in the aquifers in these delta regions, but has been shown also in several other mainly low and middle income countries.

An arsenic-contaminated tube well in Matlab, Bangladesh, being painted red as part of the mitigation programme. Photo: ICDDR,B; Dhaka

The arsenic contamination of drinking water in Bangladesh will result in hundreds of thousands of excess cancer deaths if the current exposure is allowed to continue. Steadily increasing numbers of individuals with skin lesions, diabetes, hypertension, chronic obstructive lung disease, gangrene and other arsenic-induced manifestations are reported as consequences of the catastrophe. Government and aid organisations which share a human rights perspective of safe water should without delay assist these populations. The Bangladesh population was advised by government and aid organisations to shift from the unsafe surface water to tube well water in order to reduce the burden of diarrhoeal diseases. They have the right to get arsenic-free, safe water now.

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The UN millennial goal demands greater protection of groundwater

Thomas Alveteg, MSc, Consultant, AKKADIA, and Dr Cecilia Scharp, Special Adviser, Ministry for Foreign Affairs.

In ten years, the number of people who have no access to clean drinking water and basic sanitation shall be cut by half. The big question is how this can be done in an economically, socially and environmentally sustainable way. One prerequisite is a good understanding of groundwater resources as part of an integrated water resources management. Another key factor is good planning at national and local level. But perhaps the greatest challenge is to develop organisational structures that give the different players real opportunities to influence the distribution and quality of their common water resources.

The goal of the UN is that the number of people without access to clean water and basic sanitation shall be cut by half by 2015. Photo: Sean Sprague, Bildbyrå Phoenix.

At least 1,100 million people have no access to clean drinking water, and 2,600 million have no access to basic sanitation. Contaminated water, lack of sanitation and poor hygiene – something as simple as not being able to wash one's hands – are still the chief reason that 2 million people die of diarrhoea-related diseases every year. Of these, 90% are children under five. These figures show only a few of the acute causes that have made the world resolve to make greatly increased investments in water and sanitation over the next ten years. The goal of the UN is that the number of people without access to clean water and basic sanitation shall be cut by half by 2015. This will, in turn, place greater pressure on groundwater resources and increase the risk of contamination, unless investments and construction are made in an integrated and planned manner with a large measure of local participation. Groundwater resources must therefore be put into their proper context.

Part of the hydrological cycle

Natural groundwater recharge is often a very slow process. It can take weeks, but also several hundred years.

Groundwater is part of the system of water circulation – the hydrological cycle – with clear boundaries between catchment areas. Groundwater is part of the ecosystem and constitutes the basic flow to wetlands, lakes and watercourses. The amount of precipitation and the way it is distributed in time and space, and the geological structure of the catchment area, are the natural conditions that govern the occurrence, recharge, transport and quality of groundwater.

The composition and heterogeneity of the soil strata that overlie the aquifer, the unsaturated zone, are critical for the size of groundwater recharge, and determine how much can be extracted from an aquifer without the risk of overextraction, with declining watertables as the consequence. Natural groundwater recharge is often a very slow process. It can take weeks, but also several hundred years. The unsaturated zone determines not only the size of groundwater recharge but is also the principal barrier that prevents the transfer of contaminants to groundwater. Most substances travel much more slowly than water on their way through the ground to surface water and groundwater. The reason is that contaminants are decomposed and sedimented on their way. But some substances that are transported through the unsaturated zone are stable, non-reactive compounds. Once down in the aquifer, the contaminant can be diluted to concentrations that are below the threshold values for water to be potable. The principles of groundwater protection are therefore based on calculations or estimates of transport times and concentrations in the groundwater in relation to the location of the source of contamination.

Groundwater must be protected

It is these conditions which are the reason that groundwater has often been regarded as a safe source of drinking water, even for cities of a million inhabitants such as Managua in Nicaragua and Cochabamba in Bolivia, which are completely dependent on groundwater for their water supply. One new example is El Alto in Bolivia – a rapidly expanding suburb of La Paz with about 300,000 inhabitants – which is completely supplied by groundwater. The groups of extraction wells are located downstream from the city, and the untreated discharges from small scale industry and housing pose a long term threat to the quality of groundwater. In order to effectivise water supply, a partnership has been set up between the public and private sectors. But in the agreement with the developers, there is no mention at all of issues to do with protection of groundwater and monitoring. One way of ensuring more effective groundwater protection could be to create protection zones around the wells and to make the water companies or local consumer committees responsible for groundwater protection inside these zones.

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In countries like India and China, groundwater is an important resource for both individual households and irrigation in the countryside. In the countryside, the risk of contamination is normally limited but may be a problem locally if the drinking water wells are too near a source of contamination, such as a sanitary installation. In larger communities and the poor suburbs of towns, uncontrolled sanitary installations and leaking drains can cause large scale contamination and pose a serious threat to the quality of mainly shallow aquifers. One reason for the contamination of drinking water that is often ignored is associated with transport from the well and storage in the home. From a health perspective, it is therefore important to analyse the entire chain from the protection of the groundwater resource to the way the water to be consumed is protected.

Safe distance from sanitary installations

The threat of contamination that can be chiefly associated with sanitary installations is microbial contamination (pathogens in the form of bacteria, viruses and parasites), nitrogen in the form of nitrates, and chloride. Both nitrate and chloride are normally stable compounds, especially in oxygen-rich

Purifying an aquifer is both difficult and very expensive, and in many cases it is therefore not an option.

environments, and persist in the soil for extended periods. Stable and persistent contaminants are difficult to deal with from the standpoint of drinking water. Purifying an aquifer is both difficult and very expensive, and in many cases it is therefore not an option. Microbial contamination is decomposed over time, and it is therefore mainly a threat to shallow aquifers.

The fundamental principle for the protection of local aquifers is therefore to ensure that there is sufficient distance between the sanitary installation and the well, so that there is time for the contaminant to be decomposed before it reaches the well. Normally, the half life of bacteria in groundwater can be up to twelve days, even though certain pathogens such as salmonella have been found to persist in major concentrations for up to 42 days. UNICEF has produced simple guidelines which do not demand advanced modelling, with e.g. recommended safe distances between sanitary installations and wells to ensure that there is time for microbial decomposition.

One important link in a strategic approach to groundwater protection is to construct environmentally sustainable sanitary solutions, ecosanitation. In such solutions, nutrients from toilets are used in cultivation which reduces the risk of chemical contamination. Development of ecological sanitation has accelerated in recent years. Promising examples of ecological solutions at large scale which also deal with microbial contamination are to be found in e.g. China, Uganda and Mexico.

Integrated planning at local level

Where water supply and sanitation used to be separate projects, integrated solutions are now sought.

The integrated water resources management plans (IWRM plans) which were a commitment entered into at the Johannesburg World Summit in 2002 provide a framework for the management of groundwater with the help of integrated planning. The work on drawing up national IWRM plans is very ambitious. Many governments are very uncertain about the concrete benefits of such planning. One more manageable way could be stepwise local strategic planning in which all players and the consumers of a certain water resource would work together in a local committee where the needs, problems and the relationships between the water resource and other activities are defined. Integrated planning at local level can identify users and polluters, and can assist these groups to find ways of protecting their common resource.

In recent years it has been more usual in the countryside for small scale water supply schemes and investment in sanitation to be joined up. Where water supply and sanitation used to be separate projects, integrated solutions are now sought. This implies that protection of catchment areas and direct protection of well groups is integrated already when a new water supply scheme is planned. This integrated approach reduces the risk of microbial contamination of groundwater by e.g. latrines. In order to achieve sustainable results, it is essential to engage the local population and local organisations in the work as early as possible. The great challenge is to find locally adapted models which show how water supply and groundwater protection is to be integrated and managed by the same organisations. The work should be integrated in the local water committees and the local water companies.

This integrated approach reduces the risk of microbial contamination of groundwater by e.g. latrines.

Water charges can prevent contamination

New methods of local groundwater protection have been tested with interesting results for the future. These are based on paying for environmental services and involve local cooperation between users and polluters. The principle is that the user of water in a certain catchment area pays for access to clean water. The money is used to compensate the polluter, for instance a farmer upstream who uses cultivation methods that contaminate the water. He is given money to cover the cost of changing his farming methods so that the discharges are reduced and groundwater recharge increases. This model has been successfully tested in Costa Rica and also in Nicaragua at small scale, where it has been found that consumers are wiling to pay for access to clean water.

The challenge is to produce simple but effective analytical tools in which the advantages of preventive work can be clearly balanced against the costs of solving problems when they have already occurred.

Preventive work means that the costs to society are considerably smaller than the cost of dealing with the consequences in the form of lower water tables, contaminated aquifers and reduced groundwater recharge. This is particularly important in poor developing countries with limited economic resources. The difficulty is that many developing countries do not consider that they are able to undertake such strategic planning when their own resources are mainly used in finding short term solutions to acute problems. The long term strategic and sustainable solutions are put off. The challenge is to produce simple but effective analytical tools in which the advantages of preventive work can be clearly balanced against the costs of solving problems when they have already occurred. Groundwater protection must also be integrated in the spheres of responsibility of the water companies. The costs of protection measures to secure good water quality should in due course become a natural part of water charges and tariff systems, since protection of the water resource guarantees that the consumers have access to water of good quality.

Many of the engineering solutions and models for effective groundwater protection are already available. But perhaps the greatest challenge is to develop effective organisational structures and institutions which give the different players real opportunities to make decisions and to influence the distribution and quality of their common resources.

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The Aral Sea case

Changing coastal groundwater systems around shrinking seas

Professor Georgia Destouni, Department of Physical Geography and Quaternary Geology, Stockholm University.

Changes in natural water flows after mega hydrologic-agricultural engineering in the 1960s have led to desiccation of the Aral Sea, desertification and pollution of the region at large, and deterioration of ecosystems and human health and welfare. Under present conditions, groundwater is the only remaining natural resource with potential to meet demands of safe freshwater in the area. The dramatic sea shrinkage after 1960, however, has also affected the groundwater system in the region and ongoing research efforts are directed to clarification and quantification of these effects.

The present state of the Aral Sea and its surrounding land region constitutes one of the worst environmental disasters seen in the modern world. Photo: Roger Turesson, Pressens Bild.

The Aral Sea, the Caspian Sea and the Dead Sea are all examples of inland seas that have undergone considerable water level change and shrinkage in modern time. The water level in the Caspian Sea, for instance, decreased by three metres from the 1930s until 1977 (estimated to be the Caspian Sea's greatest decrease in 400 years), but has thereafter largely recovered. More recent and ongoing sea level decrease, shrinkage and salt enrichment occur in the Dead Sea and most dramatically in the Aral Sea.

The northern half of the Aral Sea is located in Kazakhstan and the southern part in Uzbekistan. In 1960, the Aral Sea was the world's fourth largest inland water body with a water surface area of over 66 000 km^2 and a water volume of about 1 070 km^3. After major engineered river flow diversions, made in the 1960s primarily for irrigation purposes, the Aral Sea has so far lost 75% of its water surface area and 90% of its water volume. Due to this dramatic shrinkage, the Aral Sea is now split into three almost separate salt lake systems: the small Aral to the north and the western and eastern parts of Large Aral to the south. The western and the eastern part of Large Aral are now only connected by a narrow and shallow channel. In the shrinking process, the salinity of the Aral Sea has increased from its former brackish lake salinity of 10 g/l in 1960, reaching the mean ocean salinity of 35 g/l in the early 1990s, to present salinities of 90 g/l in the western part and 160 g/l in the eastern part of Large Aral. The present state of the Aral Sea and its surrounding land region constitutes one of the worst environmental disasters seen in the modern world.

Engineered changes in natural water flows

The rivers discharging into and feeding the Aral Sea with fresh surface water are Syr Darya in the north (discharging into the present Small Aral) and Amu Darya in the south (discharging into the present Large Aral). The dramatic shrinkage of the Aral Sea after 1960 reflects an order of magnitude decrease in total river discharge into the sea, from about 180 km^3 per year in 1960, to about 15 km^3 per year in 1996, due to river flow diversions of mega-hydrologic-agricultural engineering in the 1960s.

The drastically reduced discharge contributions from the Amu Darya and Syr Darya rivers have in turn dramatically increased the relative importance of fresh groundwater discharge into the Aral Sea and its present three-lake system. Groundwater discharge into the Aral Sea has changed from 12% of total river discharge into the sea in 1960 to about 100% of total river discharge at present. In addition to the importance of groundwater for human freshwater supply, the groundwater flow component has thus also become increasingly important for the overall Aral Sea water budget, which ultimately controls the fate of the present lake system.

Interconnected flows through various water systems

The Aral Sea is an example case of inland seas in dry climates, where evaporation of water to the atmosphere constitutes the main water outflow from the sea, as illustrated in Figure 1. A steady sea level is then maintained as long as the main evaporative water outflow is balanced by an equal total inflow of water to the sea from streams, rivers, groundwater and precipitation directly on the sea surface. If the total inflow of water to the sea decreases, for instance due to damming that diverts water from inflowing rivers for hydropower and irrigation purposes, the sea level, volume and surface area must also decrease until the evaporation of sea water equals and balances the new reduced total freshwater inflow to the sea.

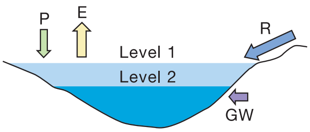

Figure 1. Schematic illustration of water balance changes. Water inflow/outflow components are precipitation P, evaporation E, river/stream flow R and groundwater flow GW. Decrease in inflow, for instance in river flow R, yields an excess outflow by evaporation E, which decreases sea water level and sea water volume.

The water balance condition differs somewhat in inland seas and lakes with main water outlets besides evaporation. Decrease in inflow to such seas and lakes may be balanced by a corresponding decrease in outflow through their outlets, with essentially maintained or only slightly changed evaporation, that is without leading to any major sea/lake shrinkage. The general condition, however, is that all flows into and out of a sea or lake are interconnected and must be balanced in order to maintain steady water level, volume and surface area. Any decrease in water inflow may lead to sea/lake shrinkage if it cannot be fully balanced by a corresponding outflow decrease in the sea/lake outlets and thus yields an outflow excess. Outflow excess will deplete the sea/lake until the evaporation outflow component, which decreases with decreasing sea/lake surface area, has decreased sufficiently to reach a new state of balanced inflows and outflows.

Groundwater flow to or from a shrinking sea or lake will also change due to water pressure changes brought about by the shrinking process. The changed groundwater flow may then constitute an essential component for balancing other water inflows and outflows and determining when the sea shrinking ends.

The coastal groundwater system around shrinking seas

The salt content of a shrinking sea increases continuously because salt is retained in the sea while water evaporates. Salt water has greater density than freshwater. Salt seawater intrudes therefore into and mixes with fresh coastal groundwater. The inland extent of this salt water intrusion and mixing zone depends on the prevailing seaward flow of fresh groundwater: the greater the seaward fresh groundwater flow, the smaller the inland extent of seawater intrusion.

On the one hand, the increasing salt content of a shrinking sea thus increases seawater density and thereby the pollution risk of fresh coastal groundwater due to density-driven inland seawater intrusion. On the other hand, however, the lowering of sea-level changes water pressure conditions towards increased seaward fresh groundwater flow, which counteracts density-driven seawater intrusion.

Quantification and prediction of the dominant cause-effect relations that determine the resulting state and changes in coastal groundwater systems under different conditions requires complex computer simulation of density-driven groundwater flow and dissolved salt transport in the coastal region, coupled with fresh groundwater flow into the coastal region from the entire upstream hydrologic drainage basin. In turn, realistic and site-specific simulation results require input of a range of different hydrologic and hydrogeologic observation data. In particular for the inaccessible and highly variable groundwater system, such data may unfortunately be largely lacking or have important gaps in both developing and developed countries all over the world.

The Aral Sea case

There are strong reasons to be careful with increased groundwater mining in the Aral Sea region.

There are strong reasons to be careful with increased groundwater mining in the Aral Sea region, in order to avoid further environmental stress on the Aral Sea itself and deterioration of fresh groundwater resources due to increased salt water intrusion. Even though the sea surface lowering, in itself, may decrease the risk of salt water intrusion, the increasing salt content and water density of the Aral Sea increase the potential for density-driven seawater intrusion.

Recent research indicates important regional variations around the Aral Sea coast with regard to both submarine groundwater discharge into the sea and the vulnerability of coastal groundwater to seawater intrusion. For the flat topography of the mostly inhabited south-eastern Aral Sea region, which includes the irrigated Amu Darya delta, the submarine groundwater discharge into the sea may have decreased and have a higher salt content compared with pre-1960 conditions. For the steep coastal topography of the essentially uninhabited north-western Aral Sea region, the submarine groundwater discharge may be increasing and the vulnerability of coastal groundwater resources to seawater intrusion may be decreasing as the Aral Sea shrinks.

Sustainable development of groundwater resources for meeting regional freshwater demands requires better understanding and quantification of the regional variability of fresh groundwater status around the Aral Sea coast, vulnerability to seawater intrusion and inter-dependence on and co-development with the Aral Sea itself. This requires, in turn, an extended and improved hydrologic, hydrogeologic and water quality data base and development of a modern information system for handling and openly disseminating this data. Costs and benefits of such water information developments must then be considered as integral parts of future water resource development and management plans and decisions in the Aral Sea region, as well as in other parts of the world.

Global concerns

From dwindling rivers and disappearing lakes and seas to military threats over shared resources, water is a cause for deep concern in many parts of the world. The amount of water in the world is finite. We are growing fast in number and our water use is growing even faster. Global water consumption has increased sixfold in the last century – at more than double the rate of population growth – and goes on growing as farming, industry and domestic water demand increase.

We are growing fast in number and our water use is growing even faster.

A third of the world's population already lives in water-stressed countries. By 2025, this is expected to rise to two-thirds. The very thing needed to raise funds to tackle water scarcity and quality problems in poor countries - economic development - requires yet more water to supply the agriculture and industries which drive it. A UN-backed World Commission on Water estimated in 2000 that an additional $100bn a year would be needed to tackle water scarcity worldwide. Even if the money can be found, spending it wisely is a further challenge. Dams and other large-scale projects are judged essential for economic growth and may provide millions with water, but they already affect 60% of the world's largest rivers and have in many cases, such as the Aral Sea case, led to considerable societal and ecological costs.

Groundwater supply is at present a widely used solution for meeting water demands.

Groundwater supply is at present a widely used solution for meeting water demands, but it means living on capital accumulated over millennia, and depleting it faster than the interest can top it up. As groundwater is exploited, water tables are dropping alarmingly in many different parts of the world. Major groundwater level changes entail also changed slopes of groundwater levels, which largely determine groundwater flow directions, velocities, interactions with surface and coastal waters, and through these also water quality in all these interacting systems.

Sustainable global development requires much better understanding of and prediction capabilities for the interactions and co-dependences between engineered water systems that are designed for meeting human needs and the different natural groundwater, stream/river and coastal and marine water systems that are used for these needs and are impacted by their physical, chemical and biological consequences and waste products. Such understanding and prediction improvements cannot be achieved without serious global commitment to monitoring, quantification and openly shared information of water flow and quality trends and fluctuations and water system interactions.

As concluded also for the Aral Sea case, serious commitment means that the costs and benefits of such water information developments should in the future be explicitly considered as integral parts of water resource development and management in developed and developing parts of the world. In view of the research efforts and resources which are now spent to map and quantify everything from elementary particle interactions to the spread of matter and energy in the whole universe, it should also be possible to allocate necessary resources for relevant mapping and quantification of the so far largely neglected groundwater system and its interactions with other water resources upon which all life on Earth depends.

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Okavango River Basin

A near-pristine river under increasing pressure

Professor Jan Lundqvist, Department of Water and Environmental Studies, Linköping University, Ass professor Lotta Andersson, Swedish Meteorological and Hydrological Institute, Norrköping, and Dr Julie Wilk, Department of Water and Environmental Studies, Linköping University.

The Okavango River is the river from the “End of the Earth” to the “Jewel of Kalahari”. The basin covers portions of Angola, Namibia and Botswana in southern Africa. The pressure on this near-pristine and largely unique natural system is mounting. An augmented reliance on both surface water and groundwater is necessary to improve living conditions for the poor people. The impact on water flow in the river has been assessed in various development and climate change scenarios.

In the Kalahari Desert in Botswana, the Okavanga River forms a large inland delta where exclusive tourism has been developed. Photo: Jan Lundqvist.

Figure 1. The Okavango River and its basin comprise parts of three countries in southern Africa. The Delta is located in Northwestern Botswana, in the Kalahari Desert.

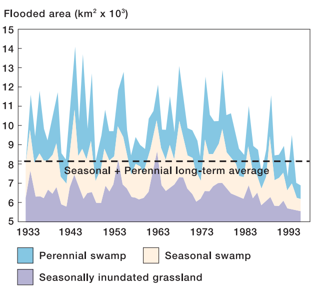

Figure 2. Variation in the areal extension of the perennial swamp, seasonal swamp and the seasonally inundated area of the Delta. Source: Ashton (2000b)

The Okavango River, its tributaries and catchment constitute a highly dynamic hydrological ecosystem and society complex in southern Africa (Figure 1). In hydrological terms, the river is endoreic, i.e. it forms a closed system where the water does not reach the sea but ends its journey in a huge wetland in the middle of the Kalahari desert. The river is exotic in the sense that almost all of its flow is generated in the headwaters in the relatively high rainfall areas of central Angola, while the downstream areas are semi-arid and arid. A temporal variation in rainfall results in a noticeable fluctuation in the river flow and also in the area inundated or reached by water, seasonally as well as between years (Figure 2). With reference to the interface between society and natural resources, the Okavango River and large parts of its catchment area are still in a near-pristine state. As a result of low human pressure and natural circumstances, the water is generally clear and of potable quality.

"The flow of a lifeline"

The river has aptly been referred to as the "flow of a lifeline" (Mendelsohn and el Obeid, 2004). Figures about the population living in the basin are uncertain and vary between 0.6 million to about 1.1 million, depending upon how the area of the basin is defined. The river basin is also highly appreciated by a large number of wealthy tourists and environmental organisations, especially the flora and the fauna inherent in the spectacular, lush Delta, located in the northwestern part of Botswana. The myriad of life and the dynamics of this green oasis – often referred to as the "Jewel of the Kalahari" – is nourished by about 9 to 10 km^3 of water and an estimated 490,000 tonnes of sediments that annually emanate from the upper reaches of the basin. Three small rivers and channels fan out in the Delta from the main river and meander over a vast and virtually flat desert landscape, with a gradient of about 1:10,000. The total active catchment is about 110,000 km^2 with an additional 45,000 km^2 with only occasional contributions to the river flow. The Delta varies in size from some 2,500 to about 14,000 km^2 (Figure 2).

But the "peaceful dynamics" that now prevails may change. It is only relatively recently that the unique character of the basin has become subject to mounting national and international interest. Its peripheral location in combination with a perceived poor resource endowment has resulted in a lack of intervention from outside. In Angola, that part of the basin has been referred to as *terras do fim do Mundo*, the Portuguese expression for "the place at the end of the earth". All the three capital cities of the riparian countries are located far away from the basin. There are no known mineral deposits in or near the basin and soils are generally of modest or poor quality. Currently, there are formal constraints against exploitation. The Delta became a Ramsar site in 1996, actually the largest designated Ramsar site in the world. Ramsar Convention on Wetlands of International Importance seeks to promote international awareness and cooperation in the conservation of threatened wetland ecosystems (www.ramsar.org).

The inevitable change is coming closer

Like elsewhere, change is the most certain thing to occur in the basin, but foretelling what it will entail is extremely difficult. For all those who face overt poverty in the basin, the opportunities that the water resources represent can hardly be overlooked. But even if needs are pressing, the most realistic prediction is that planned and large-scale interventions will be slow to come. The remote location of the basin also means that basic infrastructure is missing and, hence, investment requirements for rapid change are staggering. The war-affected people will, however, return to their former homesteads in the basin and contribute to an altered land and water use. Further downstream, in Namibia, the demand for the Okavango waters includes plans to divert part of the flow down to Windhoek, the capital city, but also an expansion of the irrigated area in the vicinity of the river. In Botswana, the idea to protect the Delta is strong and fuelled by articulated concerns from the international community. But the possible utilisation of the water resources in the Delta for something else than the natural flora and fauna cannot be ruled out.

Most of the probable interventions are supposed to result in reductions in the amount of water that is left to flow in the lifeline. It is also relevant to ponder over the possible hydrological impacts of climate change, a factor which lies outside the control of regional stakeholders. Another threat in this category is tectonic activity. Should it occur, it could entirely alter the paths for river flow in downstream areas with disastrous consequences for the Delta.

A better understanding of the likely impacts from human interventions in the basin is important as a basis for realistic planning. As it is now, "explanations" about perceived or assumed changes in water flow, which are very poorly substantiated, are common among people in the basin and also figure in newspapers and other media reports.

Current pressure is concentrated on surface water

In spite of the geographical location of substantial parts of the basin in a dry or very dry area, the withdrawal of water for various activities in society is surprisingly limited. Most of the abstractions from the river take place in the Kavango region, that is, along the 400 kilometre stretch of the river where it passes the north-eastern part of Namibia. But even if the precious Okavango water is withdrawn for the most water intensive activity in society, i.e. irrigation, the abstraction is only about 1/4 of a per cent of the water that, on average, pours into the Wetlands of the Delta.

Figures on the amount of water withdrawals are, however, deceptive. For instance, even if the amount of water withdrawn from the Delta is much less than the corresponding volume withdrawn in Namibia, the volume of water evaporated from the Delta is significantly much larger. Since evaporation and transpiration, in practice, mean a withdrawal of water for alternative potential use it is relevant to compare the various use options of the water available in the river basin and to relate them to livelihood and environmental objectives.

Reliance on groundwater is increasing

With population growth and development aspirations, there is a need to look for livelihood opportunities also in sites located at some distance from the "lifeline". With the prevailing land use system among small-scale farmers, the gradual impoverishment of the soils forces people to move to new sites for cultivation, often at some distance from the river. The possibility to utilise groundwater has therefore become important. Through the assistance of the Department of Water Affairs, an estimated 500 water points have been built. More significant, however, is the growing number of wealthy farmers who have drilled private wells and installed pumps in the Kavango region. In all, the large farms covered an area of over a million hectares in 2002, i.e. quite a significant acreage.

Very little is known about the total utilisation of groundwater in the basin. Some important features can, however, be mentioned. The Okavango, like other endoreic rivers located in drylands, is vulnerable to disturbances. The fate of the Aral Sea is a dramatic case in point. In Namibia and Botswana, there are no perennial tributaries feeding the main river. But ephemeral rivers and shallow aquifers consisting of old channels are linked to the river. The wells that have been drilled show that some of these aquifers yield rather big volumes of water from depths varying between

10 to 30 metres and in exceptional cases even down to 350 metres. A special characteristic of these aquifers is that the underground movements of water are often towards the river. Hence, in this part of the basin, the Okavango River gains water from the shallow aquifers rather than the other way around. Tapping of groundwater therefore means that the flows to the river are reduced, which in turn means that the riparian vegetation is affected. However, there is no publicly available information about the extent of the aquifer flow into the river, and since the new farms are at some distance from the river, the impact from this kind of development is uncertain. Changes in riparian vegetation are also caused by in situ activities.

Generally, the climate in the lower part of the basin is characterised by sequences of wetter and drier years of about ten year cycles. In Botswana, the most prevalent coping strategy in past times of drought has been to dig wells. It is likely that this strategy will be important also in the future. The extent to which this has influenced groundwater reserves is unknown but could be of consequence if the trend escalates. In addition to rural areas, water supply to Rundu in Namibia and Maun, a small but thriving tourism centre at the lower end of the Delta, comes from ground water sources. There are also speculations about significant volumes of groundwater south and south east of the Delta.

What about the future?

As part of a recent EU financed research project dealing with the Okavango river basin, a hydrological model was used to assess the impact of various development and climate change scenarios on downstream river flow (Andersson et al., 2005). In consultation with key decision makers in the region and with input from representatives of UN organisations and development cooperation agencies, including SIDA, the intention was to lay the foundation for the use of scenario modelling as a tool for water resources management in the Okavango basin. The relative significance of various development scenarios on river flow and variation over time could be compared with the likely impact of climate change, as determined by a number of global climatic models under different greenhouse gas emission scenarios.

Three development scenarios were identified and important parameters quantified: Low impact, Business as usual and High impact. In the low impact scenario change in water demand was supposed to be due primarily to population and livestock increase. This scenario was assumed to be a feasible option in combination with eco-tourism, which presumes that the natural systems are left intact. This development option could be combined with horticulture and other income activities connected with tourism, but would not include irrigation and similar water intensive activities. Business as usual included some irrigation schemes, deforestation in a buffer zone of 1 kilometre along the river and its tributaries, and construction of one hydropower station, in addition to population increase. In the high impact scenario all areas estimated as suitable for irrigation, about 1,040 km^2, were supposed to be developed, and a buffer of 2 kilometres along the river would be cleared. Moreover, the Eastern National Carrier would be operational, i.e. an abstraction of water to Windhoek and the central parts of Namibia. The High impact scenario should be seen as estimates of the highest possible impact of various developments, not as realistic future predictions.

Assessment of impact from alternative development options

The runs of the model revealed some important results. The impact on downstream flow from the low impact scenario was very limited. Over a 20-year period, the annual river flow was reduced by 0.1%. Given the significant natural fluctuation, this impact would not make any difference. Also, the impact from the business as usual scenario was modest. Implementation of irrigation schemes mentioned in official reports would decrease annual flow by 2%, while deforestation in a 1 km buffer zone would increase flow by 2.5%. Downstream hydrological impact of the construction of one upstream hydropower station would be insignificant in terms of annual flow and with a slight increase of low season flow. The high impact scenario resulted in a maximum reduction in downstream annual flow by 8%, with a reduction in minimum monthly flow of 17%. Deforestation, which is part of the scenario and related to an expansion of irrigation and other development interventions, would increase the flow by 6%. Depending upon the operational rules of the hydropower reservoirs, the change in the flow distribution over the year could, however, be significant, but the impact would only be significant during wet years.

Compared to the three development scenarios, the impact from a climate change is far greater, although the uncertainty in these predictions is considerable. A number of reports point at a likely climate change in the region (Tarr, 1999; Arnell, 2003). The effects are likely to be rather modest for the first half of the century. For the 2050–80 period, the average estimate from the tested climatic models and emission scenarios indicate a reduction in the mean annual flow into the Delta of about 20%, which may increase to about 25% for the 2070–99 period.

A tremendous challenge

With an increasing interest in the Okavango River and its basin, the pressure on this near-pristine and largely unique natural system is mounting. An augmented reliance on surface as well as groundwater resources is necessary to improve living conditions, which are appallingly low for a large part of the population. Increased withdrawals of water and a higher consumptive use will be detrimental to the fantastic natural flora and fauna in the Jewel of Kalahari. But there are similar jewels, green, pulsating and living, in other parts of the basin, which are of significant importance in various respects, from an environmental point of view but also as a basis for livelihood.

An augmented reliance on surface as well as groundwater resources is necessary to improve living conditions, which are appallingly low for a large part of the population.

The conventional thoughts about "development" have been close to the business as usual or the high impact scenarios, indicated above. Although the assessed impact on river flow from these two development options is smaller than what is often thought, the combination of human interventions and possible climate change make the low impact scenario an interesting option. It holds the promise of a "win-win" situation, i.e. improving livelihoods by providing income earning opportunities in activities that are low in water demand. The challenges to facilitate and implement this development option are of course tremendous. But so are all other development options.

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Windhoek, Namibia

Effective groundwater management in arid regions

Professor Gilbert Svensson, Chalmers University of Technology, Göteborg.

In Namibia, dry periods occur frequently, and at the same time water consumption is rising. In order to increase water availability, sewage effluent is now being re-used, both directly and through recharging the groundwater reservoir. The sewage is first treated by advanced methods which includes membrane filtration. It is now time for many countries in Africa to adopt this technology in order to safeguard their water supply.

Namibia is the most arid country in southern Africa. Photo: Nigel Charman, Pressens Bild.

Economic growth in Namibia is hampered by water supply problems, which are chiefly a problem of water availability.

Namibia is the most arid country in southern Africa. Dry periods occur often, followed by a shortage of water. The central parts of Namibia and the capital Windhoek are far from the available sources of surface water, which are rivers in the north and south near the frontiers with neighbouring countries. Economic growth in Namibia is hampered by water supply problems, which are chiefly a problem of water availability.

Water supply to Windhoek is today based on surface water which is collected in dams, and on groundwater which is abstracted from the Windhoek aquifer. The latter has been used since 1911 and two boreholes are still in production, one from 1928 and one from 1939. The Windhoek field is most important for water supply in connection with dry periods. In recent years water shortage has occurred more frequently than before owing to dry periods and the rising demand for water. Since the supply of surface water is sensitive to rainfall and is completely dependent on rain falling at some time during the year, Windhoek is now planning to reinforce the Windhoek aquifer by recharge through deep boreholes in addition to the surface recharge which has been in use for some time.

Reclamation of sewage is absolutely necessary to prevent diffuse discharges of sewage contaminating and destroying groundwater supplies.

Sewage is treated and recharges groundwater

People in Windhoek have realised for a long time how important it is to protect their groundwater resources. Reclamation of sewage is absolutely necessary to prevent diffuse discharges of sewage contaminating and destroying groundwater supplies. Since 1968, the sewage treatment plant at Windhoek has been using advanced methods.

The treated sewage effluent has been used both to reinforce raw water supplies directly (ca 15% of the daily demand in Windhoek) and to reinforce the groundwater supplies by recharging treated sewage effluent. The treatment plant has been repeatedly upgraded over the past 30 years, and today the fifth generation of the plant is in use. Sewage treatment is now complemented with a membrane filtration installation to achieve a high degree of purity for the water which shall be used for direct recirculation and for recharge to reinforce the groundwater supplies.

More expensive water

Annual water demand in the Windhoek area is today 30 mm^3 and is expected to rise to 40 mm^3 by 2020. Surface water supplies from dams provide a maximum of 20 mm^3 annually, while other raw water supplies give 12 mm^3 annually in normal conditions. Of this, the treated sewage effluent at Windhoek provides 5 mm^3 annually, i.e. ca 40%. In dry periods abstraction from groundwater supplies increases to 22 mm^3 annually, but these abstraction rates are not sustainable in the longer term. Recirculated water from the membrane filtration installation at the Windhoek sewage treatment plant shall provide up to 7.5 mm^3 annually when it has come up to full capacity.

The cost of water will increase by 50% over the next 10-year period, which will involve a rise in price that cannot be afforded by the poor population of Windhoek. A redistribution of the costs between the poor and the better off must therefore be incorporated into the tariffs for water.

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Programme for water and sewerage

When recharge increases and levels rise in the Windhoek aquifer, the risks of groundwater contamination by activities on the surface increase. Today, the distance to the groundwater in the areas where artificial recharge is being planned is about 120 m, and it is estimated that this distance will decrease to about 30 m. The quality of the water that is injected through deep boreholes must also be closely monitored to ensure that the quality of the groundwater reservoir is not jeopardised.

In order to reduce the risks of contamination from the ground surface, Windhoek has introduced a programme for the supply of ”informal settlements” with both water and sewerage. When new informal settlements are established, the inhabitants are contacted to form a local council that is given the responsibility for both water and sewerage inside a small area. In return, Windhoek connects the area to both water and sewerage. As the economy of the area develops, Windhoek begins to levy charges.

The health risks of re-using sewage effluent to produce drinking water are managed by ensuring that not more than 35% of the distributed water comes from the reclamation plant, and also through an intensive metering programme. The proportion of the production cost accounted for by the intensive metering programme is about 30%.

Time to re-use sewage effluent

Re-use of water and artificial recharge of groundwater are resorted to all round the world today. This is an accepted technology for balancing demand and supply of water in areas where there is a shortage of natural water supplies. For many different reasons, the use of this technology is still in its infancy in many

African states. It is however time for this technology to be adopted to the benefit of many towns and their populations. With sound knowledge and well planned projects, this technology can be a viable option for water supply in arid regions.

The Nile Valley

Excessive irrigation threatens pharaonic monuments

Associate Professor Per-Olof Johansson and Anna-Jeanette Larnelius, MSc, SWECO.

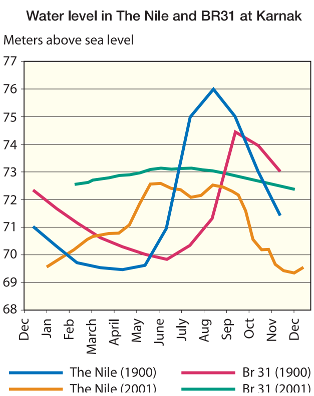
The Aswan High Dam was constructed in the 1960s and has resulted in increased hydroelectric production, protection against flooding, greater agricultural production and better river transport. But it has also had negative effects, among them elevated groundwater levels in the Nile valley. These high groundwater levels entail the risk of waterlogging and salination of poorly drained agricultural areas. They have also been found to pose a threat to many of the pharaonic monuments, among them the Temples of Karnak and Luxor at Luxor.

Considerable quantities of salt are moved up into the surfaces of the monuments, where the salt is precipitated and causes discoloration and disintegration of the surfaces. Photo: Ludovic Bouvéron.

The Temples of Karnak and Luxor are to the east of the Nile. The Temple of Karnak is 500-1000 m from the bank of the river, ca 3 km to the north of the centre of Luxor. The Temple of Luxor in the centre of Luxor is right on the Nile. Illustration: Pertti Salonen

The balanced water flow in the Nile and the increased agricultural irrigation have resulted in a balanced and, on average, higher groundwater level in the temple areas near the river. Today, the groundwater level is less than 2 m from ground level during much of the year over large areas of the temple complexes. This means that water with dissolved salts can more or less continually be transported by capillary action from the groundwater up into the monuments. The driving force for this movement is the very high evaporation. Considerable quantities of salt are moved up into the surfaces of the monuments, where the salt is precipitated and causes discoloration and disintegration of the surfaces.

The Egyptian authority responsible for the monuments (Supreme Council of Antiquities, SCA) approached SIDA in 1999 with a request for help in protecting the Temples of Karnak and Luxor. SIDA allocated funds for an investigation of how the groundwater level in the temple areas can be lowered. The task was given to SWECO which had previously worked on the preservation of various pharaonic monuments, inter alia on the moving of Abu Simbel in conjunction with the construction of the High Dam.



Variations in water level in the Nile have diminished after the construction of the High Dam, and the increased irrigation has resulted in higher and better balanced groundwater levels in the temple areas. The water levels in 1900 and 2001, both in the Nile and in a groundwater well in the Temple of Karnak (BR31), are compared. The ground level at BR31 is ca 74 m.

Water rises in sandstone and mortar

The climate at Luxor is very dry and hot. Precipitation is insignificant and temperature in the summer is often above 40°C. The potential annual evaporation exceeds 2100 mm. The agricultural areas upstream from the temples (to the east) mostly grow sugar cane which demands intensive irrigation. Annual irrigation is about 2500 mm. The water that does not evaporate directly or is not taken up by the plants is drained via a tile drain system and open ditches, or seeps down into the groundwater. Water also directly seeps down into the groundwater from the irrigation canals. The surface sediments in the Nile valley at Luxor are mainly silty and clayey. The thickness of these sediments varies from a metre or two to about 20 metres. These are underlain by sand and gravel strata down to a depth of ca 70 m. It is in these coarse grained sediments that most of the groundwater flow takes place. Owing to the seepage from irrigation, the groundwater level to the east of the temple is always higher than the level of the Nile and groundwater therefore always flows towards the Nile.

The soil strata in the temple areas have variable capillary characteristics. Most of the temple monuments are of sandstone. The sandstone has capillary rises of 1-2 m, but where mortar has been used this may act as an important transport path, with considerably greater capillary rise. It is therefore impossible to define an exact desirable minimum depth for the groundwater table which would stop capillary flow. But experience in the area is that where groundwater is never nearer than 2 m from ground level, damage is small. The objective of the protective measures must therefore be to lower the groundwater level so that this minimum depth to the groundwater is achieved.

The temple of Rameses III at Karnak is damaged and discoloured (white patches) at the lower part of the temple wall. The darker patches higher up are caused by nitrate salts and indicate the ground level before the excavations; they are not associated with the present transport of groundwater up into the monument.
Photo: Per-Olof Johansson

Little risk of settlement

Comlementary field investigations confirmed the general stratal sequence outlined above, but also revealed considerable heterogeneity. The investigations also provided data on groundwater levels in different parts of the area, the permeability of the soil strata and the risk of settlement in the clay strata. The risk of settlement as a result of groundwater lowering was an important issue. The geotechnical investigations showed, however, that the clay in the area is heavily overconsolidated. This means that the increased load which the envisaged lowering of the groundwater level causes will not result in any settlement of significance. In addition, prior to the construction of the High Dam, the lowest annual groundwater levels were on the whole lower than the levels which must be achieved by drainage. But in view of priceless nature of the monuments, an extensive monitoring programme for settlement was drawn up for both the survey and construction stages.

On the basis of the existing data and the complementary field investigations, a mathematical groundwater model was constructed for the area. With the help of the calibrated model, a number of alternative measures were tested, among them changes in irrigation which would reduce seepage into the groundwater, and engineering solutions in the form of land drains and wells. Extensive analyses were also made of the sensitivity of the model results to the uncertainty of the input parameters.

Drains and wells

During the model simulations it was found that it is not sufficient to halve today's seepage from irrigation to achieve the specified requirement for the minimum depth of the groundwater level. Because of this, together with the far-reaching consequences and the long time it would take to alter the irrigation and cropping systems, an engineering solution was considered most appropriate. The reason for the choice of the engineering options which were tested was the wish for a simple, sustainable and robust solution and a location that would minimise the direct impact in areas with ancient monuments.

The proposed solution comprised a combination of land drains and wells. The drains are mainly laid in the upper soil stratum which has lower permeability, and the wells go down to the deeper and more permeable sand stratum. At Karnak, drainage had to be installed all round the temple area. At Luxor, it was sufficient to drain to the east of the temple, both because the area is much smaller, and because hydraulic contact with the Nile here is much lower than at Karnak.

For each temple there is a main collector laid at a depth of 6-8 m below ground level. The land drains and wells empty into the main collector. This, in turn, conveys the water by gravity flow to a pumping station from where it is pumped into the Nile. The length of the main collector is approximately 5 km at Karnak and 1 km at Luxor; their diameters vary between 300 and 800 mm. The series of land drains are parallel to the main collector and are 100 m long. The 20 wells are between 30 and 40 m deep and have the form of gravel filter wells of 250 mm diameter, with a 10 m long well screen. These wells are not pumped but discharge into the main collectors. The pumping station at Karnak has a capacity of 32,000 m^3/d and the one at Luxor 8000 m^3/d. These capacities are somewhat larger than the maximum drained volumes given by the model simulations for the highest Nile levels, using the set of parameters which, in the sensitivity analysis, gave the greatest groundwater flows.

Seepage from irrigation must be reduced in the long term

Construction of the proposed drainage system started in the beginning of March 2005. Construction is financed by USAID and is carried out by Egyptian contractors. Supervision, financed by SIDA, is managed by SWECO.

This type of engineering solution is feasible for single valuable objects where there is an acute need for action. In order that the problems caused by the elevated groundwater levels in the Nile valley may be solved generally and in the long term, the source of the problem must be tackled, i.e. the large scale seepage from irrigation. This demands a comprehensive change that includes sealing of the irrigation canals, a more effective irrigation technique, and a change to crops that require less water. Such a change has wide ranging social and economic effects and needs a long time for its implementation.

Salinisation of groundwater in coastal areas

Bo Olofsson, Tech Dr, Department of Land and Water Resources Engineering, Royal Institute of Technology, Stockholm.

More than half the world's population lives inside a 60 km wide coastal zone. This increases pressure on water and gives rise to the risk of salinisation of both the soil and groundwater. But there are measures that can be taken to counteract salinisation of coastal aquifers. These are technical purification systems such as desalination and hydraulic and physical barriers. The intentions to limit water abstraction appear difficult to achieve. Development is rather towards greater use of water.

Generally, the cause of salinisation is large scale overabstraction of fresh groundwater, much greater than what can be recharged. Photo: Anders Hamnö

Brackish groundwater is a serious problem in many regions of the world. Intrusion of seawater into freshwater aquifers occurs along most of the built-up coastal areas. More than half the population lives inside a 60 km wide coastal zone where very intensive building development is taking place. Almost all the megacities of the world are inside the coastal zone. Even though large cities account for only about 10% of total freshwater abstraction, they impose a large local stress on the freshwater reservoirs.

The saltwater problem occurs all over the world, but it is naturally most serious in densely populated coastal regions where there are no real alternatives to groundwater abstraction as a source of water.

Along large coastal areas, seawater has already intruded a long way into the freshwater reservoirs. This is the case in e.g. India, Taiwan, Bangladesh, Thailand, the Mediterranean countries and the Netherlands. Saltwater intrusion as far away as 5–6 km from the coast has been reported. Generally, the cause of salinisation is large scale overabstraction of fresh groundwater, much greater than what can be recharged. In many areas where there is excessive groundwater abstraction, groundwater levels therefore steeply decline, in parts of India by 1-2 m annually. Near Manila the groundwater level has dropped by 50-80 m. Many wells have dried out and must be constantly deepened. Coastal regions in India and Thailand have been abandoned because of the lack of freshwater.

The saltwater problem occurs all over the world, but it is naturally most serious in densely populated coastal regions where there are no real alternatives to groundwater abstraction as a source of water. But even in water-rich countries such as Sweden there are local problems, for instance on islands in the Stockholm Archipelago where the natural storage facilities for freshwater are limited in extent and abstraction is extensive and seasonal.

Salt and the body

Long term consumption of salt gives rise to health effects such as damage to the kidneys and the heart. An admixture of only 1–2% seawater in the freshwater reservoir makes the water unfit for consumption over an extended period. According to WHO, daily salt intake should not exceed 5 g sodium chloride, which often implies 100–200 mg Na/litre in drinking water. Water in arid climatic regions sometimes naturally has higher salt contents even without seawater intrusion. By comparison, seawater contains about 10,000 mg Na per litre. On the other hand, it is also no good to drink deionised water all the time, since some of the salts are essential for the body.

Salt and the soil

There are also other reasons for salinisation of the groundwater apart from seawater intrusion. One reason is that there is a steep increase in the use of groundwater for irrigation. So much freshwater is abstracted from the ground that the heavier brackish water situated lower down rises up and destroys the freshwater supplies. When irrigation is carried out in hot climatic regions, evaporation causes salt to be concentrated in the infiltrating water which can percolate down into the groundwater. Irrigation with brackish groundwater destroys not only the crop but, in the longer term, also the productive capacity of the soil. Salinisation of soils is therefore regarded as by far the greatest single factor that leads to loss of agricultural production and degradation of the land. Development of irrigation techniques and alternative irrigation strategies are therefore an important field of research and development which also has a great influence on the salt water intrusion problem. Swedish and international experts are cooperating in this work.

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Locally, other sources of salt can also cause damage to groundwater supplies, for instance groundwater abstraction in the vicinity of salt deposits, evaporite formations. Anthropogenic sources such as leakage from waste deposits, industry, road salt and sewage can also damage groundwater. Locally, these effects may be very important, and in the longer term they may cause private and communal groundwater supplies to be taken out of production.

Processes in the ground

The processes underlying seawater intrusion in coastal areas have been studied for a long time, and there are several regular scientific conferences in this subject, such as SWIM (Salt Water Intrusion Meeting) which has had as many as seventeen conferences, two of which were organised in Sweden, and SWICA-M3 (Saltwater Intrusion and Coastal Aquifers – Monitoring, Modelling and Management) with two conferences to date. The proceedings from these conferences give a good description of the problem.

Brackish water has a higher density than freshwater, and it is therefore situated at greater depth. A wedge-shaped tongue of saltwater extends inland from the coast at an increasing depth below the freshwater that is recharged through precipitation. But, in reality, the general picture is a lot more complicated since the ground is mostly made up of strata of different permeabilities, formed during different epochs and in different geological environments. A thin clay horizon, for instance, can effectively prevent the penetration of new rainwater, but locally it can also act as a barrier against the rise of deeper saline water.

The stratal sequence varies from place to place, and because of this heterogeneity it is difficult to predict in detail the effects of groundwater abstraction. Natural barriers, for instance hard and unfissured crystalline rocks and strata of clay, can in certain cases effectively prevent the intrusion of seawater, while porous strata may allow effects to extend over several kilometres from the coast. Nor are groundwater conditions static; they change all the time through both natural processes and anthropogenic influences, such as groundwater abstraction, manmade barriers and subsoil drains or leaking pipes.

Climate and groundwater

Researchers are relatively unanimous that the ongoing climate change causes changes in sea level. The rise is at present considered to amount to 1-2 mm annually and to cause a general 10-90 cm rise in sea level by the year 2100. The effects on low lying coastal areas have therefore been discussed mainly with regard to the increasing risk of flooding and erosion.

What is much more worrying is that even a moderate rise in sea level will seriously affect freshwater reservoirs.

What is much more worrying is that even a moderate rise in sea level will seriously affect freshwater reservoirs. Merely because of differences in density between fresh and brackish water, a 10 cm rise in sea level will cause 4 metres of freshwater reservoirs to be lost. In flat coastal areas this can cause serious water supply problems.

How do we know what is happening?

A large number of methods have been used to predict problems due to brackish groundwater in coastal regions. Ongoing research all over the world demonstrates the scope of this problem. Water conditions in coastal areas are one of the most common applications of mathematical modelling, usually by finite element or finite difference models. Swedish researchers have also, through international cooperation, contributed their mathematical modelling know-how in recent years. What has often been the problem is that it has not always been possible to calibrate the models since there is often a lack of input data in the form of water levels, abstraction data and geographical stratigraphy data. It has therefore been difficult locally to give a correct description of the ongoing salt water intrusion. The use of satellite information and the coupling of geographical data in GIS and flow models enhances the prospects of using the models.

Methods have also been developed, inter alia in Sweden, which are based on relatively easily manageable water and mass balance calculations. There are also index methods based on the assessment of vulnerability to brackish groundwater using the charting and weighting of geographical data that can be obtained from GIS. They have the advantage that they have a simpler structure and are therefore easier to understand by decision makers. But they are static and cannot illustrate dynamic processes, for instance climate changes or changes in land use and hydrological measures. They have however been used to advantage in environments of great hydrogeological complexity, for instance in coastal areas with crystalline rocks where groundwater flows are difficult to calculate by mathematical modelling.

Groundwater is of different origins and ages

Many researchers in the world have studied the chemical changes in water quality that occur as a result of seawater intrusion. In order that appropriate methods to counteract groundwater salinisation may be selected, it is important that the causes of the elevated salt contents should be clarified. All groundwater is a mixture of water of different origins and ages. Methods are being developed to identify the origin of a brackish groundwater. Investigations connected with the final storage of nuclear waste in Sweden, Finland, Canada and other countries have provided valuable knowledge and contributed to method development. The methods are based on analyses of ionic ratios and isotope investigations with e.g. oxygen and hydrogen isotopes.

In certain cases chemical modelling can be used to advantage. Sweden has for a long time been engaged in successful cooperation with countries in Europe and Asia, where groundwater chemistry calculations are used for the assessment of groundwater origin and ongoing processes. A statistical chemical multivariate method which has been developed in Sweden has recently been used to chart the interaction between surface water and groundwater in Kerala, India. An investigation of a canal shows, inter alia, that tidal effects causing elevation of salt content in the canal extend for several kilometres into the canal which, in turn, has a great effect on surrounding aquifers.

Measures to prevent salinisation

Measures to prevent salinisation of coastal aquifers can be classified as water purification systems (chiefly desalination), hydraulic and physical barriers, and sociocultural measures. The latter are primarily intended to limit the magnitude of water abstraction and to lead to more effective utilisation of the water resource. But these intentions are counteracted by building development in coastal regions which have the result rather of increasing groundwater abstraction.

Methods for desalination of seawater have been used for a long time. Some areas, for instance the Canary Islands, are completely dependent on such plants. The present desalination plants are generally based on membrane separation (reverse osmosis). They demand a lot of maintenance and are expensive, but have the advantage of also removing other nondesirable components from the water. Sweden is in an advanced position in research concerning membrane separation for different purposes.

Hydraulic barriers, such as treated sewage water, can counteract ongoing seawater intrusion. By means of mathematical modelling, appropriate infiltration systems can be designed and groundwater conditions balanced. In India and other places, subsurface dams have been used for a long time for the storage of groundwater and surface water which would otherwise rapidly drain away after the monsoon period. Effective methods for rainwater harvesting have been developed in arid climatic regions. A feedback of such experience and knowledge to Scandinavia has occurred for application in certain coastal areas with limited aquifers and large seasonal groundwater abstraction, for instance in the Stockholm Archipelago where subsurface dams for the collection and recharging of rainwater have been constructed.

Groundwater-seawater interactions in the Mediterranean region

Carmen Prieto, PhD, Department of Land and Water Resources Engineering, Royal Institute of Technology, Stockholm.

Seawater intrusion is a major problem and the dominant threat to the intensively exploited coastal aquifers in the semi-arid Mediterranean. A challenging question for the management of groundwater resources in coastal areas is: how can an increasing water demand be satisfied and the seawater intrusion problem controlled at the same time? One of the investigated strategies comprises desalination of brackish groundwater combined with artificial recharge of the aquifer with treated wastewater.

How can an increasing water demand be satisfied and the seawater intrusion problem controlled at the same time? Photo:Bartolomé Balaguer, Pressens Bild.

In the southern part of the Mediterranean Sea, water is a scarce resource, but as everywhere on Earth it is a resource essential for life and development. Due to irregular distribution of surface water resources, many coastal areas and islands in the Mediterranean basin are dependent on groundwater resources for their water supply.

Seawater intrusion

Seawater intrusion is in fact a major problem and likely the dominant threat to the intensively exploited coastal aquifers in the semi-arid Mediterranean.

The achievement of a sustainable balance between water demand and water supply is a major challenge for the management of water resources in the Mediterranean region due to the general trend of increase in water demand from population, agriculture and tourism and the limited renewable freshwater resources. The southern part of the Mediterranean basin is characterized by arid and semi-arid climatic conditions, with natural recharge from precipitation varying greatly over the year and extended periods of no recharge. Additionally, in these areas, the summer period with the lowest water availability is the period of highest water demand from intensive tourism and irrigation activities.

This common negative temporal correlation in availability and demand of fresh water causes seasonal water stress problems, which are usually solved by a temporal increase in groundwater abstraction rates. Increasing the abstraction rates in coastal aquifers disrupts the fragile equilibrium existing between the fresh groundwater flow towards the sea and the seawater inflow into the aquifer. As a consequence, the freshwater/seawater interface may start moving landward contaminating some of the available fresh groundwater resources. This groundwater contamination problem is known as seawater intrusion. A mixture of only 2% seawater (salinity ≈ 35000 ppm TDS -Total Dissolved Solids) with freshwater (salinity of 100 ppm TDS) makes the extracted groundwater unsuitable for drinking purposes (salinity limit for drinking water is 500 ppm TDS according to the American Environmental Protection Agency), and 5% makes it unsuitable for irrigation, excluding some salt tolerant crops.

Seawater intrusion is in fact a major problem and likely the dominant threat to the intensively exploited coastal aquifers in the semi-arid Mediterranean. A challenging question for the management of groundwater resources in coastal areas is: how can an increasing water demand be satisfied and the seawater intrusion problem controlled at the same time?

Trying to fill the gap between supply and demand

The role of non-conventional freshwater sources such as seawater desalination and re-use of wastewater are becoming more important, but they are still minor water supply sources. Seawater desalination is now primarily used in places where no other sources are available like the Balearic Islands in Spain and some Greek islands in the Aegean Sea. The reason is that although desalination is cheaper now than it used to be, it is still considerably more expensive than the conventional sources, i.e., groundwater or surface water.

Treated wastewater may be directly re-used for irrigation or recreational purposes, as in Spain. Or it may be recycled as groundwater (artificial aquifer recharge) with the objective of increasing the hydrologic budget of the aquifer, which can also counteract seawater intrusion, as is done, for instance, in Israel and Cyprus. However, the use of treated wastewater is currently limited, because it is not generally accepted by the public.

Another possible water supply strategy may be transfer from other regions or basins. However, such water diversions may have serious consequences as seen for instance in the Aral Sea case, which is discussed in another article in this book.

Sustainable groundwater management in coastal areas

Recent research efforts have been directed to investigating the cost and efficiency of a groundwater management strategy that comprises desalination of brackish groundwater (water of slight to moderate salinity, from 1000 to 10000 ppm TDS) combined with artificial recharge of the aquifer with treated wastewater. This possible groundwater management strategy has been investigated in three different coastal aquifers located in the Eastern part of the Mediterranean Sea. Results show that such a strategy for water supply in seasonally-stressed and semi-arid coastal regions may be cheaper than seawater desalination, which would be an alternative strategy to meet increasing water demands.

The main advantages of the novel coastal groundwater management strategy are:

- The treatment costs associated with desalination of brackish water are about one-third lower than those for seawater. Moreover, the strategy has an additional advantage for areas with limited energy supply because the required energy input to desalinate brackish water is lower than that for seawater.
- Instead of being discharged to the sea, artificial recharge of treated wastewater has the dual benefit of controlling the

seawater intrusion problem and enhancing the hydrologic budget of the coastal aquifer.
- Acute saltwater intrusion problems are avoided because the water artificially recharged into the aquifer damps the impact of seasonal water stress.

In general, desalination of brackish groundwater may be economically viable and re-use of wastewater can be more widely applied when the public's perception improves. This requires more research in order to assess the best ways to artificially recharge aquifers and to understand the effects of different qualities of treated wastewater. At present, there are no uniform quality standards for the re-use of waste water, for instance at European level, and waste water is treated to different degrees in different countries according to national guidelines.

Groundwater discharge to the sea

Groundwater is discharged to the sea as a mixture of freshwater from the coastal aquifer and re-circulated seawater from tides, waves and density and thermal differences that force seawater into the sea bottom. This mixture is known as submarine groundwater discharge. The fresh water component of submarine groundwater discharge may be considered a loss of fresh water resources, specially in semi-arid regions. However, it is extremely important to have a certain amount of fresh groundwater discharging into the sea because it counteracts seawater intrusion into the aquifer.

In total, submarine groundwater discharge is estimated to contribute to a considerable amount of freshwater inputs to the Mediterranean Sea. This is due to the fact that highly water conductive geological karst formations comprise 60% of the shoreline. A large number of submarine springs have been detected in some parts of the Mediterranean Sea. For instance, near the coast of Greece, 400 m off Argolikos Bay and at a depth of 72 m below sea level, freshwater has been collected from spring Aqualos. Total submarine groundwater discharge may constitute a new source of freshwater provided that it can be easily captured. If the discharge is not completely fresh, it may anyway be cheaper to desalinate than seawater. Another possibility is to capture the discharge before it reaches the sea. This approach has been used in Japan, where underground "dams" have been constructed to hinder channelized submarine groundwater discharge in volcanic or karst terrains.

In addition to freshwater, submarine groundwater discharge, whether it is a widespread or diffuse flow through the sea bottom or springs, may carry a significant amount of dissolved nutrients and other pollutants to the sea. Such pollutant discharges have traditionally been overlooked. When an aquifer undergoes saltwater intrusion, for instance, some pollutants that may be absorbed in the porous material of the aquifer can be released, and subsequently be transported and discharged into the sea, contaminating the receiving coastal waters. A relatively novel challenging research question is then how much groundwater and possible associated pollutants are discharged into the sea.

At present, submarine groundwater discharge is an emerging and exciting interdisciplinary field of research with mainly hydrologists, hydrogeologists and marine scientists working together for an understanding of how submarine groundwater discharge influences the biological and chemical processes in the coastal ocean.

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Groundwater in Khao Lak after the tsunami

Jenny Lindgren, MSc, IVL Swedish Environmental Research Institute Ltd.

On 26 December 2004, several waves of tsunami swept over the coasts in South-East Asia. There was extensive destruction in countries such as Indonesia, India, Sri Lanka and Thailand. In Thailand alone over five thousand people were killed and thousands of people were made homeless. Now those who continue living in the affected areas are also facing other problems, one of which is the intrusion of saltwater into groundwater. A Swedish team from IVL, together with representatives from Thailand, has charted the situation in Khao Lak – one of the worst hit areas in Thailand.

The saltwater problem in the wells will be much less serious during the rainy season. Photo: Filip Moldan

The earthquake that caused the tsunami in South-East Asia was the second largest in modern times. When the Indian plate was forced beneath the Burma plate in the Indian Ocean in the morning of 26 December, the tremor registered 9.3 on the Richter scale. The earthquake generated gigantic waves which rapidly travelled across the sea. When the waves reached the west coast of Thailand and Khao Lak, they were up to 13 m high. The water swept in over the land and destroyed houses, infrastructure, power lines – everything in its way. The salt seawater ran down the wells dug in the soft sandy soil and filled open surface water reservoirs.

People in Thailand soon became aware of the problem of unsafe drinking water. In the coastal province of Phang Nga alone where Khao Lak is situated, an area of about 585 square kilometres was flooded by the waves and most of the wells became unfit for use. There was very quickly a shortage of clean drinking water, and water had to be brought in from e.g. Bangkok. In January, a water plant from Sweden, run by the Swedish Rescue Service, was installed. In the meantime, new wells were dug, but even in these the water was often brackish and largely unfit as drinking water.

Surveying in the tsunami zone. Water level was measured in every well and related to sea level.

The department for surface and ground water of the Thai Ministry of Environment, in cooperation with IVL, has carried out an investigation of the water situation in Khao Lak, financed by SIDA. The investigation began in March 2005 and comprises charting the scope of contamination of surface and ground water in Khao Lak and in the fishing village Ban Nam Khem.

Reservoirs were filled with salt water

Water supply in Khao Lak is mainly based on communal or privately dug wells for household uses and laundry. Well water is seldom used as drinking water, because of the worry that it may be contaminated by bacteria from lavatories and the defective sewerage system. Along the coast in Phang Nga, tin has been extracted from the ground for a long time, and a large number of opencast mines are today used as reservoirs for surface water which after treatment is used as drinking water. The two largest reservoirs in Khao Lak have volumes of 700,000 and 300,000 m^3 and are managed by the community. Water is treated by precipitation, sand filtration and disinfection. Both reservoirs were filled to the brim with salt water on 26 December and the water became undrinkable.

Sea salt chiefly consists of sodium and chloride ions, and it is the concentration of chloride ions that is measured to determine whether or not the water is saline. In Sweden, the limit value for salt in drinking water is 100 mg/l; in Thailand the limit is 200 mg/l. Up to 600 mg/l is said to be acceptable, even though the water then tastes very salty. The standard limit for taste is a chloride ion content of 300 mg/l of water.

Water supply in Khao Lak is mainly based on communal or privately dug wells. Photo: Jenny Lindgren

After the tsunami, the two main reservoirs in Khao Lak, Nong Kok and Nong Mun Takva, were filled not only with salt seawater but also all the material that the wave brought inland. People have worked for a long time to empty the reservoirs of water so that all that has ended up there may be removed and transported away – parts of buildings, cars, bodies, mud and rubbish. People are trying to dig away about one metre from the edges and the bottom, but the work is hard and it is not possible to empty these large reservoirs completely. Nong Kok, which is the source of water for more than 700 families, is as large as a small lake.

Annual precipitation in Phang Nga province is about 3500 mm. The dams are now being filled with rising groundwater and all the rainwater that falls during the first rainy period after the tsunami. Both the dams are situated just at the edge of the tsunami zone, and the water that drains from the areas upstream will not be saline.

Dug wells are hit hardest

Most wells in Khao Lak are dug wells of 4-8 m depth, constructed with concrete rings and often without a base. Some hotels and municipal installations could afford to drill cased wells to depths of more than 50 m. The water is used sparingly for household purposes; running water is seldom available. Some wells are fitted with a simple pump that lifts the water up to a large water tank on the roof; this acts as a small water tower. In many cases water is raised manually by bucket. Abstraction of water is mostly limited, and problems due to saltwater intrusion from the sea because of heavy abstraction have therefore been unusual.

When the tsunami swept in over the coast, seawater ran down into the dug wells and infiltrated into the ground. Bored wells escaped this if they were so well sealed that no saltwater ran down into the well. Groundwater in bored wells is abstracted from the rock, and this has not been affected by saltwater from the tsunami. In order to chart the groundwater situation in Khao Lak and the fishing village Ban Nam Khem, about 60 wells 25 km to the north of Khao Lak, both dug and bored ones, were sampled. Some wells were sampled before the tsunami. The results show that salt contents vary widely depending on distance from the coast, whether the well had been filled with seawater, how high upland the well was situated, and how long the area around the well was flooded.

Many people living in villages near the coast are worried that water is undrinkable because of salt content. One woman in the fishing village Ban Nam Khem says that she cannot use the water even to wash herself – all the salt makes her itch. In the worst wells, water has chloride ion concentrations up to 2500 mg/l – this can be compared with seawater which contains ca 20,000 mg chloride ions per litre. When the groundwater was sampled before the rainy period in April, it was noted that in some places new wells had already been dug near the old ones. The water in the new wells was often at least as saline as in the old wells. This indicates that the groundwater reservoirs near the old dug wells have become saline.

Bacteria make the water unsafe

Sewerage in particular is a serious problem in the area, and even before the tsunami it was unusual for people to use their own well water for drinking.

The community is now being rebuilt at a fast pace, and in many cases the inhabitants have neither the time nor the inclination to wait for new rules and planning regulations from the authorities. In Ban Nam Khem, where more than 80% of the village was washed away, houses are built in the same way as before the tsunami, and there is nothing to indicate that water supply and sewerage will be constructed in a different and better way from that before. Sewerage in particular is a serious problem in the area, and even before the tsunami it was unusual for people to use their own well water for drinking. The wave destroyed many sewers, and dirty and infected water leaked into many of the wells.

An investigation of bacterial concentration in wells in the area found that some wells contained faecal bacteria, which shows contamination by sewage. According to Swedish codes, water is then unfit for drinking. Some wells even had such high contents that they were unsuitable for washing clothes. In one of the villages people were so worried about bacteria that water in the village was used only to mix concrete for rebuilding the houses. This was the right decision; in one of the wells we found a lot of bacteria.

Some wells were also sampled above the area hit by the tsunami, and here also there are problems due to infiltration from defective sewers. The problem of bacteria in the wells will not be resolved before a properly working sewerage system is constructed. Analytical results from April 2005 show that contamination of wells continues. The only way to tackle this problem is to remediate the source of contamination, and then dig out and disinfect the well before it is used again. One possible solution is for all houses to be connected to a common sewage treatment plant. This is a huge challenge and primarily a matter of cost. Just now the population gives priority to rapid reconstruction that must not cost too much.

Metals are no major problem

The area is rich in metals and mining has been carried on for a long time. An analysis for metals was therefore made in some wells and reservoirs, for zinc, cadmium, mercury, lead, iron and others. The contents of iron and manganese in some wells were above the limits laid down in the Thai drinking water standard. This is not related to the tsunami and can be relatively easily remedied, for instance by aeration of the water.

One effect of the tsunami is that the concentration of sodium ions is unusually high. A high sodium content causes hypertension. People who take medication for high blood pressure are recommended not to drink water with more than 20 mg of sodium per litre; in the saline wells up to 240 mg/l was found. The concentrations of other metals in wells and reservoirs are not high.

Rain will eventually cleanse the groundwater

The mean annual precipitation in the coastal area around Khao Lak is 3500 mm. This is to be compared with the mean annual precipitation of ca 650 mm in Sweden. All the rain in Khao Lak mostly falls during six months, April to October, when rainwater percolates through the sandy soil. Water flushes out the chloride ions in the top soil strata and dilutes the saline groundwater which is slowly moving towards the sea. Rainwater, supplemented with large quantities of runoff from the nearby mountains to the east, will naturally cleanse the groundwater.

Due to the fact that reservoirs were rapidly pumped dry after the disaster and the high precipitation, the problem of salinated groundwater will probably be resolved by natural cleansing already during 2006. The problem of saltwater in wells will considerably decrease during the rainy season, and water will probably be fit for laundry and household purposes as early as 2005. The two large reservoirs in Khao Lak which supply many people with drinking water can very probably be used again after the rainy period. Many of the small private reservoirs which were not pumped dry and cleaned will remain unusable until they have been pumped and cleaned.

When wells and sewerage systems are constructed in the same way as before, the risk remains that drinking water will be unsafe due to bacteria.

Villages and hotels in Khao Lak are being rebuilt; people in Thailand hope that tourists will come again no later than one year after the disaster. People want to move home from the temporary emergency camps, and new houses are built quickly and not always subject to control. When wells and sewerage systems are constructed in the same way as before, the risk remains that drinking water will be unsafe due to bacteria. Sampling of groundwater will continue in 2006 to check that salt contents decrease. The authorities want to take overall charge of water supply and sewerage systems in conjunction with reconstruction in the area to ensure that standards are better in future.

Metals in groundwater – arsenic is the most serious problem

Professor Gunnar Jacks, Department of Land and Water Resources Enginering, Royal Institute of Technology, Stockholm, Professor Marie Vahter, Institute of Environmental Medicine, Karolinska Institute.

If we contaminate groundwater, it takes a long time before it is pure again. Since metals have "eternal life", it is very important that they should not penetrate down into groundwater. While most metals present no major problems, arsenic has become a problem in many areas in the world. In Bangladesh alone, perhaps 60 million people are exposed to contents that are above the WHO guideline value of 10 µg As/litre. The high prevalence of arsenic-containing groundwater is mostly a natural phenomenon; arsenic is a constituent of the bedrock.

Well water containing arsenic poisons people in Bangladesh. Photo: Paul Hansen, Pressens Bild.

Every one of us uses large quantities of metals in consumer products. However, per capita use varies greatly. For example, in industrialised countries ca 10 kg copper per person is used annually, while in parts of Africa the amount is one hundredth of this. Anthropogenic metal contamination of groundwater is however generally greatest in low income countries, since many are primary producers of metals and also because their industries have less well developed process technologies.

Elevated concentrations of heavy metals are not commonly found in groundwater. Organic matter, humic substances and clay minerals are negatively charged and have great capacity to adsorb heavy metals which are often positively charged ions, for example Zn^{2+}, Cu^{2+} or Cd^{2+} (zinc, copper and cadmium). Adsorption by humic substances increases as the pH value of the soil rises. But in acid soils metals can easily find their way down into the groundwater. Metals such as copper, lead, zinc and cadmium occur as sulphides in the lithosphere. When the sulphides are exposed to air they are oxidised, and sulphuric acid is produced. Acid leachate from mine tailings is a global problem, but it is most serious when it poses a threat to surface water, rivers and lakes. Very large adsorbing mineral surfaces are exposed in the groundwater environment, and heavy metal contamination is not very common. When it does occur, it is often associated with soil that has become acid through sulphide oxidation.

Metals or metalloids which form anions (negatively charged) are often bound less tightly to humic substances, clay minerals and organic matter, and in such cases pH dependence is reversed – the higher the pH value, the lower the adsorption. It is primarily oxides or hydroxides of iron and aluminium that are positively charged at low pH values, and can then adsorb e.g. chromate or arsenic in the form of arsenite or arsenate. Chromate, arsenite and arsenate are oxyanions; this means that the metal is combined with oxygen, and the whole ion is negatively charged.

The health effects of arsenic

Arsenic in groundwater has become a serious problem in many parts of the world because of the widespread natural mobilisation of arsenic in groundwater.

Arsenic is a metalloid which has been known as a poison since antiquity. Acute poisoning became less prevalent after the use of arsenic in pigments was banned in the 19th century. On the other hand, arsenic in groundwater has become a serious problem in many parts of the world because of the widespread natural mobilisation of arsenic in groundwater. This may occur even when the concentration in the soil is not particularly high. Arsenic in groundwater is probably the most serious exposure to metals today. Epidemiological investigations have shown serious health effects at relatively low exposure levels. In Bangladesh alone, it has been estimated that 30 million people use drinking water with concentrations exceeding the local drinking water standard, 50 µg/litre, and perhaps twice as many above the WHO guideline of 10 µg/litre.

The toxicity of arsenic when it is ingested in high doses is well known. But arsenic can also cause serious health effects on chronic exposure to low doses. The earliest symptom, which often occurs after several years of exposure, is pigmentation changes and hyperkeratosis, i.e. thickening of the outer horny layer of skin, mainly on the palms and soles. What is however more serious is that arsenic is a potent carcinogen and that, after many years' exposure via e.g. drinking water, it can cause tumours in the skin, lungs, bladder and kidneys, and possibly also in the liver. This has been shown in a number of epidemiological studies in e.g. Taiwan, Chile, Argentina and India. Associations between arsenic exposure and increased prevalence of peripheral vascular damage, liver damage, diabetes and hypertension have also been reported.

Arsenic passes the placental barrier and the fetus has approximately the same blood concentrations as the mother. There are only a few reports on the effects of arsenic on fetuses and small children, and it is not possible to estimate the health risks due to exposure during the early development of the child. However, a recently published experimental study suggests that prenatal exposure results in a higher cancer risk than exposure during adulthood. Arsenic is excreted to only a small extent into breast milk. Breast feeding therefore protects the child from arsenic exposure in cases where the nursing mother ingests arsenic via e.g. drinking water. A few minor investigations suggest that the psychomotor development of the child is affected, but more data is needed before the risks can be reliably assessed.

A recently published experimental study suggests that prenatal exposure results in a higher cancer risk than exposure during adulthood.

Susceptibility varies

Susceptibility to arsenic may be influenced by the individual's nutritional status. A low intake of vitamins and essential minerals, for instance selenium, appears to increase the risk of health effects due to arsenic. This is probably partly due to the antioxidative effect of nutrients, i.e. that they provide protection against the oxidative stress in the tissues caused by arsenic. The nutritional status of the individual also affects the metabolism of arsenic, which, in turn, influence the toxicity.

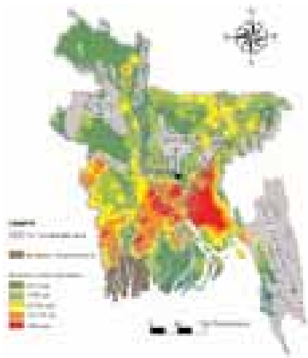
Inorganic arsenic is metabolised in the body through methylation, which results in the formation of metabolites of both higher and lower toxicity. Variations in the metabolism may therefore contribute to the inter-individual variation in susceptibility. The concentration of arsenic in the urine is often used to determine ongoing exposure. This analysis requires a methodology that distinguishes between the metabolites of inorganic arsenic and the considerably less toxic organic arsenic compounds, for instance arsenobetain and various arsenosugars, which are often present in fishes and crustaceans. For the determination of previous (days to months) exposure, the arsenic content of hair can be used.

WHO recommends that drinking water should not contain more than 10 µg arsenic/litre, and this is the drinking water standard in both the EU and USA. Many countries still have 50 µg/litre as the threshold value, because high concentrations are of common occurrence. The lifetime risk of cancer due to daily intake of drinking water containing 10 µg/litre, corresponding to an intake of 10-20 µg of arsenic per day, has been estimated at ca 0.3%. It is therefore desirable to limit the intake of arsenic as far as possible. This applies particularly to children, since experimental studies suggest that fetuses and small children are more susceptible than adults. There is a lack of risk estimates regarding the chronic effects of arsenic in children.

Arsenic in groundwater in Bangladesh

The Bengal delta in which the rivers Ganges, Brahmaputra and Meghna debouch is a deep depression in the bedrock caused by the collision of the Indian Plate with the Eurasian Plate during the Tertiary Era. It is filled by compacted sediments up to 20 km in thickness. These sediments largely derive from the slopes of the Himalayas. Weathering annually loosens 1,700 tonnes of sediment which is deposited in the delta. It is the mineral grains, often covered with red iron hydroxides, which have moderate amounts of arsenic adsorbed on them. In the delta, with its meandering branches, this sediment is deposited together with organic matter. The southern part of the delta is today covered in mangrove swamps. It is likely that during the Holocene these were of considerably larger extent. The sediment is thus “sandwiched” with organic matter, sometimes peat strata. This peat is decomposed bv bacteria, and the sediment becomes anoxic. When the oxygen has been used up, decomposition of the organic matter is taken over by bacteria which use the iron in the iron hydroxides as an oxidising agent. The iron is then transformed into soluble divalent iron, and the adsorbed arsenic is released.

In view of the fact that the sediment contains ca 10 mg arsenic per kilogram and that the threshold limit for arsenic is 10 µg/litre, i.e. 0.1% (one thousandth), toxic groundwater can arise almost anywhere at all if the groundwater basin is anoxic. The arsenic contamination of groundwater is therefore, in all essentials, a natural phenomenon. It is possible that an increase in rice cultivation will in the long term aggravate the problem since it creates anoxic environments. When rice is grown in saturated soil, the oxygen is consumed in decomposing plant residues. Irrigation with arsenic-containing groundwater is also a serious long-term problem which results in a slow accumulation of arsenic in the soil and a gradual increase in the crops. Taro (family Araceae), a tuber crop usually eaten by the poorer sections of society, is already high in arsenic.



Map of Bangladesh with the three large rivers Ganges, Brahmaputra and Meghna. The map shows geomorphology and arsenic contents in groundwater. Data from British Geological Survey (2001) processed by Mattias von Brömssen at Royal Institute of Technology, Stockholm.

Sediments in the Bengal delta are highly variable, and wells with arsenic containing water are often found close to wells with low concentrations. In most cases, deep wells have water with low arsenic concentrations since the arsenic is usually bound in sulphides. If the mosaic of sediment layers with brown to red oxidised sediments can be mapped, it is probable that new wells with low arsenic contents can be drilled with good accuracy.

Arsenic in groundwater in other parts of the world

Release of arsenic into groundwater under anoxic conditions occurs in many places in river deltas and sediment-filled valleys, especially in South and South-East Asia. The Red River in North Vietnam which owes its name to the red sediment it carries is an example. Arsenic has also been found in groundwater in Pakistan, Nepal, Thailand, Cambodia, Myanmar, Inner Mongolia in China and Taiwan.

As stated above, arsenic occurs as an anion adsorbed on aluminium and iron compounds in sediments. Under alkaline conditions, adsorption decreases and the arsenic can be dissolved into the groundwater. This is another type of arsenic prevalence in groundwater which is found in Argentina and elsewhere. In such a case, arsenic is accompanied by fluoride which is also mobilised at high pH values in the soil and in groundwater basins.

Chromium-rich groundwater near tanneries

Chromium is an essential metal which interacts with insulin, but is toxic on high exposure. Exposure of the airways gives rise to cancer, while chromium via water and food produces variable toxic effects, for instance modification of DNA. Chromium is used in the production of steel, metal finishing and the tanning of leather. It is chromium in the form of chromate (negatively charged ion) which is the more troublesome form owing to its mobility in the soil and groundwater. In India there are extensive problems due to byproducts from metal finishing. Chromate can be reduced to trivalent chromium that is strongly adsorbed in the soil or forms insoluble solid phases. In India, due to the hot and dry climate, the organic matter content of the soil is low. Adsorbents in the form of iron hydroxides occur in large quantities in the red tropical soils, but the pH value of the soil is often high and it has little adsorptive power. Concentrations up to 30 mg/litre in the form of chromate have been measured at depths of 20-40 m in groundwater in Ludhiana, a large industrial city with cycle industries in Punjab in the north of India. The WHO threshold limit value is 50 µg/litre.

Tanning of leather has been largely exported to developing countries. China and India are large producers of tanned leather. In actual fact, chromium in byproducts and waste should not occur as chromate, since chromate is reduced by organic matter. It should instead occur as less mobile trivalent chromium. But this has been found not to be true in e.g. semi-arid areas with low organic matter contents. In these places, manganese oxides can oxidise reduced chromium to chromate. In Tamil Nadu in the south of India, there are large tanneries and the groundwater can have chromium contents of up to 50 mg/litre.

What can be done?

Groundwater is the largest freshwater resource in the world if we disregard the polar ice sheets. The turnover time of groundwater globally is of the order of 300 years. If we contaminate groundwater, the time for ”recovery” is even longer since the water interacts with surfaces contaminated by metals.

What has surprised us is that nature does not always provide us with good groundwater. The extensive occurrence of arsenic containing groundwater is largely a natural phenomenon. We still know too little of geochemistry and biogeochemistry in the groundwater environment. Not least, we need to learn more about the redox processes which, to a large extent, govern the occurrence of iron, chromium and arsenic in groundwater.

What has surprised us is that nature does not always provide us with good groundwater. The extensive occurrence of arsenic containing groundwater is largely a natural phenomenon.

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Pesticides in groundwater – two examples from Africa

Professor Henrik Kylin, Norwegian Institute for Air Research, Mr. Ralph Meinhardt, South African Bureau of Standards, Professor Michael Kishimba, University of Dar es Salaam, Tanzania, and Professor Henk Bouwman, North-West University, South Africa.

To produce cash crops, pesticides are needed to a much higher degree in the tropics than in the temperate zones. When this need to use pesticides is coupled with low education among the users it's a perfect basis for environmental problems. However, the highest risk of pesticide contamination of water resources, including groundwater, is often not the direct use in agricultural fields, but point sources and "old sins". An additional problem is that substances that have been phased out in industrialised countries are still used in many parts of the world.

In many developing countries small farmers use an excess of pesticides. Many farmers spray once a day or more. Photo: Sean Sprague, Bildbyrå Phoenix.

Pesticide contamination of groundwater is widespread all over the world where pesticides have been used. The chemical and physical properties of a compound determine how it will behave in the environment, e.g., if it will end up in any specific environmental compartment such as the groundwater. Obviously there is an interaction between the chemical and physical properties of the compound and the chemical and physical properties of the environment. In the case of groundwater the properties of the soil have a great influence on the fate of a contaminant. In tropical countries, soils that are not regularly subjected to flooding are usually old and weathered compared to the soils in the temperate regions where there have been recent glaciations. Old and weathered soils often have a low capacity to retain contaminants such as pesticides. Therefore, pesticides may reach the groundwater with comparative ease.

Point sources the highest risk

Of course, there is always a risk when a chemical is wilfully introduced into the environment that the chemical will turn up in a place where it was not intended. Unfortunately, in many developing countries, small farmers often use an excess of pesticides. Many farmers spray once a day or more. Such practices are mostly due to lack of education and environmental awareness, poor information about the proper use of pesticides, and the risks involved with the use. Furthermore, excessive use of pesticides gives little benefit to the farmer in the form of increased crop protection. Instead it increases the risks both of development of pesticide resistance in the pests and contamination of food and water resources. And it does so at a high economic cost to the farmer!

However, the highest risk of pesticide contamination of water resources, including groundwater, is often not the direct use in agricultural fields, but point sources. Such point sources may be places where pesticides are stored, where spraying equipment is filled and cleaned, or where unintentional releases have occurred. We will describe two cases from our own experience where pesticide contamination of groundwater gives rise to problems with human health and crop production. Although one is actually a case of wilful use of pesticides, the result is that a point source has been created that now contaminates the local water resources.

Vikuge State Farm in Tanzania

The first example is one of many similar on the African continent. In 1986, Tanzania obtained a consignment of 170 tons of pesticides as a gift from a private company through the Greek government. The pesticides were placed in a storage shed at Vikuge State Farm, 60 km northwest of Dar es Salaam, with the intention to distribute the pesticides to other farms. However, many of the pesticide containers were empty already upon arrival and many of the containers were of household size, difficult to use in agriculture or vector control programmes. Even worse, the labelling on many containers was in Greek only. As few farmers in Tanzania read Greek, it's a very vivid illustration to the proverb "It's all Greek to me". Whatever other documentation may have been attached to the consignment is nowadays missing. We know from photographs of pesticide packaging found at the site in 1989 that the consignment contained telodrin, an organochlorine insecticide that was discontinued by the producer in 1965, more than 20 years before the donation, because of its high toxicity.

The pesticides that arrived from Greece to Vikuge State Farm in Tanzania were placed in a simple storage shed that soon collapsed and left the pesticides unprotected under the open sky. Photo: Börje Paulsson

There was the insecticide telodrin among the donated pesticides. The production of this substance was stopped in 1965, more than 20 year before the donation, because of its high toxicity. Photo: Börje Paulsson

The storage shed soon collapsed and the pesticides were left unprotected under the open sky. A bushfire went through the area in 1995 creating ideal conditions for the formation of even worse contaminants than the pesticides. In 1996 the visible remains of pesticide packaging material were scooped up and placed in a new storage facility. However, the site where the original storage shed was located is still devoid of all vegetation. When one visits Vikuge, there is at times a pungent smell of pesticides, and insects that happen to land on the bare soil drop down dead.

High levels of pesticides in soil and wells

When we investigated the soil at Vikuge we found extremely high levels of pesticides in the bare soil where the old storage shed once stood. The topsoil contains up to 30% DDT and 6% lindane! Both DDT and lindane are organochlorine insecticides and highly persistent in the environment. There were also several other pesticides present at very high levels. The presence of these contaminants is in itself disturbing. But even worse, when we looked in detail at the composition of both the DDT and the lindane they seemed to be depleted in the insecticidal component. The technical products of both DDT and lindane are mixtures of several different compounds of which only one has the desired capability to kill insects. In most of the samples we took at Vikuge, the concentration of the specific insect killing compound was low as compared with the other compounds in the technical mixtures. Now, 20 years later, it is difficult to prove anything, but the disturbing suspicion arises that much of the donation was in fact low-grade pesticides or waste from pesticide production.

The villagers at Vikuge get their water mainly from two shallow wells that both contain pesticides above the WHO-recommendations. Some villagers complain that the water has a chemical smell and taste, and may give rise to headaches and nausea.

The problems do not end there. The old storage shed was placed on top of a small hill. Consequently, during the torrential rains of equatorial Tanzania, the surface runoff contains high concentrations of pesticides so that the pesticides will contaminate an even larger area. The groundwater is rather close to the surface and is also contaminated with pesticides. The villagers at Vikuge get their water mainly from two shallow wells, simple holes dug in the ground downhill from the contaminated site. When we measured the concentrations of pesticides, both wells contained pesticides above the WHO recommendations. Some villagers complain that the water often has a chemical smell and taste and that it may give rise to headaches and nausea. To somewhat alleviate the problems, water is also trucked to a cistern close to the farm for distribution to a tap in the village. Unfortunately, the PVC pipe that distributes the water from the cistern to the tap runs straight through the most contaminated area, and we found high concentrations of pesticides in the tap water also.

The World Bank recently initiated the "African Stockpiles Project" with the intention to remove from Africa old stocks of pesticides that cannot be put to any good use. The programme will likely include Vikuge. Unfortunately, the project does not make provisions for any clean-up of contaminated sites. It will remove the remains in the new storage facility, but leave the contaminated soil. Although it is highly motivated to remove the old packaging material in the new storage facility, it is, in our view, relatively well protected and the smaller of two problems. The contaminated soil is a much bigger problem. If nothing is done to remediate the site, the soil will continue to contaminate the water resources for the villagers in Vikuge for the foreseeable future.

Limpopo River Valley

The border between South Africa and Zimbabwe runs along the Limpopo River. As part of the border defence, South Africa during the 1980s erected a sisal barrier hedge parallel to the river in the area east of Messina in what is now the Limpopo Province. The hedge was constructed between cultivated fields and the Limpopo, usually 10–50 m from the river.

The Limpopo River Valley is a major vegetable production area in South Africa. Although the climate is dry, it has a good supply of irrigation water from the Limpopo. The river itself has an interesting flow pattern. During the dry season, which obviously also is the irrigation season, most of the water flows 2–4 m under the surface of the riverbed. The farmers make use of a system where trenches are dug or bore holes are drilled in the riverbed from which water is extracted for irrigation.

As part of the hedge maintenance, herbicides were used between the sisal hedge and fences on either side. Very high doses were applied each year for approximately 10 years. Urea herbicides were used and probably also triazine herbicides. Both these classes of herbicides are taken up from the soil via the roots and inhibit photosynthesis. Experience shows that they may also persist for many years in groundwater due to low microbial activity.

Crop damage and herbicides in groundwater

Six years after the first use of herbicides along the hedge the vegetation at the riverbank started to deteriorate. The initial damage was yellowing and death of leaves on trees and scrubs, symptoms typical of the herbicides used along the hedge. Shortly after the first damage a massive dieback of branches and plants occurred. At the same time vegetable farmers experienced drastic yield reductions not due to any problem inherent in their agricultural practices. Yields decreased steadily to the extent where certain fields had to be abandoned. Yields were initially good in the new fields, but soon crop damage occurred there also. This was a consequence of the increasing levels of herbicides in the arable soil as the irrigation water brought a constant supply of herbicides from the river to the fields.

Six years after the first use of herbicides along the hedge the vegetation at the riverbank started to deteriorate.

When we investigated the problems we found that herbicides that had been used in the sisal hedge had leached downwards to the groundwater and then been transported with the groundwater flow to the underground Limpopo River. We could also show that it was the same herbicidal substances that had been applied along the hedge barrier that were the cause of the crop damage. The irrigation water brought a constant supply of the herbicides from the river to the fields and the crop damage was a consequence of the increasing levels of herbicides in the soil. The effects were first seen in the vegetation along the riverbank as it draws its water directly from the groundwater flowing towards Limpopo. The hedge itself was not affected as sisal is one of few plant species that are resistant to the herbicides that were used.

The irrigation water brought a constant supply of the herbicides from the river to the fields and the crop damage was a consequence of the increasing levels of herbicides in the soil.

Conclusions

Environmentalists in industrialised countries should remember that agriculture in the tropics is quite a different matter than in temperate climates. There are many more pests, especially insect pests, that may cause problems in the production. To produce cash crops, pesticides are needed to a much higher degree in the tropics than in the temperate zones. When this need to use pesticides is coupled with low education among the users it's a perfect basis for environmental problems.

Countries in the north have taken advantage of the relative lack of education about the risks with old pesticides to get rid of environmental problems at home.

Much of the problems with pesticides in groundwater and pesticide pollution as a whole in developing countries are due to the low environmental awareness, coupled with "old sins". Substances that have been phased out in industrialised countries are still used in many parts of the world. And, as the case of Vikuge Farm shows, countries in the north have taken advantage of the relative lack of education about the risks with old pesticides to get rid of environmental problems at home.

The case of the pollution of the Limpopo River is not primarily due to ignorance, but that what were judged as national security interests were given priority over environmental concerns. However, the dosing of herbicides along the hedge was excessive. Whether this was done in ignorance or just to be sure to kill invasive plants, the farmers along the Limpopo are now paying the price.

Modern pesticide regulations in industrialised countries call for extensive testing before a new substance is registered. However, the information gained is not necessarily relevant to tropical conditions and the pesticides may behave in unexpected ways. An additional problem for farmers in the tropics is that the protective clothing that is available is usually not designed for work under the tropical sun. To bring about a better environmental situation with regard to pesticides in developing countries, it would be useful to have more tests of new pesticides under the relevant climatic conditions. But it is also of the utmost importance that the farmers are given the necessary education to use the pesticides they need in an environmentally safe manner. Development of protective clothing that works in the tropics could be a way to increase the general awareness of problems related to pesticides. It would show the individual users of the pesticides that they should protect themselves. Hopefully such awareness could then be expanded to the realisation that they need to protect not only themselves, but also their families and the environment in which they live.

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Nutrient loadings in groundwater _ threat from agriculture and sewage

Professor Lars Bergström, Department of Soil Science, Swedish University of Agricultural Sciences.

Developing countries are today using three times as much nitrogenous fertiliser as 30 years ago, and have substantially increased their food production. But the price of the increased use of fertilisers are the risks of contaminating groundwater. Nutrients from agriculture contribute to contamination of groundwater so that it is no longer fit for drinking. Nutrients from defective sewage treatment plants also reach the groundwater. Another threat comes from irrigation with sewage effluent.

Nutrients can reach the groundwater from agriculture and from inadequate treatment of sewage. Photo: Jean-Léo Dugast, Bildbyrå Phoenix.

When we speak of nutrient loadings in groundwater, we mean enrichment of the water with plant nutrients, usually nitrogen (N) and phosphorus (P). It is primarily nitrogen, in the form of nitrate, which has received a lot of attention. Nitrogen is supplied to the cultivated soil in relatively large quantities through commercial fertilisers, manure and other organic fertilisers, and nitrate is highly mobile in the soil. Phosphorus is usually much less mobile in the unsaturated zone and therefore, in the normal case, it does not pose a major problem. Neither does potassium (K), the third important macronutrient in crop farming, present a major problem as regards groundwater contamination. On the other hand, potassium chloride (KCl) which is used quite a lot in agriculture may cause undesirable quantities of chloride to accumulate in the groundwater.

There is no doubt that the intensification of agriculture in the past 50 years has greatly contributed to the improvement of food supply in the world, but it has in many cases resulted in an increasing threat to groundwater supplies. There are a large number of studies which describe the relationship between the increased intensity of agriculture in Europe and North America and the rising nitrate concentrations in groundwater. This has raised anxiety even in many developing countries since their agriculture is of great importance for both the country's economy and the livelihood of the individual farmer. Apart from agriculture, inadequate treatment of sewage can also be a source of nutrients in groundwater.

Shallow aquifers in Africa

The most important reason that the nutrient load in groundwater is considered a serious problem is the significance of groundwater as the source of drinking water. In rich countries such as the US, more than 95% of the rural population depend on groundwater for their daily drinking water requirements. In Asian countries such as Pakistan, China, Bangladesh, Indonesia, Thailand and Vietnam, the corresponding figure is about 50%. In India more than 80% of the rural population is dependent on groundwater, in most cases taken from wells with primitive manual pumps.

A situation similar to that in Asia also prevails in many South-American countries, while the situation in Africa south of the Sahara is somewhat different. The reason is that in large parts of Africa the rock has low permeability for water, and very shallow aquifers must therefore to a large extent be used for drinking water. This has great significance for both the available quantities and quality in view of the contamination caused by nutrients in the water.

Is agriculture a threat to groundwater?

When the effect of agriculture on groundwater is assessed, several factors must be considered. Land is often cultivated over very large areas, and this has a potential impact on groundwater over extensive regions. But it is important to remember that diffuse leakage from arable land is much less intensive than localised discharges from many industrial activities. Concentrations of e.g. nitrate in groundwater in excess of what is permitted in drinking water directives, as a consequence of arable farming, are however quite common. If the groundwater is to be used for irrigation or cooling in industrial processes, the concentration of nutrients is not such a serious problem as when it is to be used for drinking.

Treatment of groundwater to lower the concentrations of e.g. nitrate is expensive, and therefore in many developing countries this cannot be done. In such cases other options must be sought, which also involves expenditure. Deeper aquifers can, for instance, be used as a source of water, and this solves the problem in the short term. On a longer time scale, this deep groundwater will also be contaminated unless the problem of nitrate leakage from agricultural land is solved – in other words, this only buys time. The final solution is to deal with the fundamental problem, i.e. to minimise the risk that nitrate will be transported down into the ground.

Nitrate concentration in groundwater is governed by many factors

The greatest increase in the use of nitrogenous fertilisers in recent years has in actual fact occurred in developing countries, where their application on agricultural land is now three times that in 1975. This has resulted in a substantial rise in food production. In Asia, 25% of the increase in rice production can be ascribed to greater use of fertilisers. In Central and South America and in some areas in South-East Asia, the use of nitrogenous fertilisers has increased because, with the help of irrigation, three crops instead of two can be harvested every year. But the increased use of fertilisers has its price, and there is reason to believe that the problem will be accentuated in the future in many developing countries owing to the increased need for food. Apart from the intensity of fertiliser use and crop farming, the magnitude of the problem also depends on the thickness of the unsaturated zone and on its permeability to water, and on the intensity of rainfall and irrigation.

The greatest increase in the use of nitrogenous fertilisers in recent years has in actual fact occurred in developing countries.

One further factor which is significant for the quantity of nitrate that will reach the groundwater is denitrification, that is to say the conversion of nitrate into nitrogen compounds which are lost to the air. One prerequisite for denitrification to occur is that conditions should be anaerobic, which may be the case in many poorly drained soils. Rice cultivation which is carried on over large areas of Asia occurs under conditions that indubitably promote denitrification. This is the reason that the concentrations of nitrate in the groundwater in rice growing areas are often low, even though there is relatively extensive use of nitrogenous fertilisers.

There are also other reasons that nitrate reaches the groundwater, even though the use of nitrogenous fertilisers in agriculture is considered to be the most important of these. There are geological deposits of nitrogen-rich minerals, such as saltpetre in Chile, which probably contribute to high concentrations of nitrate in groundwater. In semi-arid regions, for instance in the north of Africa, there are elevated nitrate concentrations in groundwater which are considered to be due to deposits of nitrogen-fixing vegetation, for instance Acacia, in the soil profile. Nitrogen from these deposits has been transported through the unsaturated zone for several thousands of years and has in this way got into the groundwater. Further causes of elevated nitrate concentrations may be irrigation with sewage effluent, leakage from manure heaps, intensive animal husbandry around wells and atmospheric deposition of nitrogen.

Sanitation problems

A serious contributory cause of the presence of faecal matter, and thus plant nutrients, in groundwater is that there is a shortage of good sanitary facilities in developing countries.

A serious contributory cause of the presence of faecal matter, and thus plant nutrients, in groundwater is that there is a shortage of good sanitary facilities in developing countries. Even when there are septic tanks, these must be emptied regularly; this does not always take place and in many cases the effluent from these tanks is allowed to percolate in the surroundings. The provision of sanitary facilities varies from country to country, and even within countries. It has been estimated that about 2,600 million people in the world have no access to sufficiently good treatment of solid waste from lavatories, especially in the countryside in large parts of Africa.

Each person excretes about 4 kg of nitrogen annually, and it may be assumed that a high proportion of this nitrogen is oxidised to nitrate and can thus contribute to contamination of groundwater. But there are conditions that can alleviate this risk. Denitrification has been referred to above as one way of lowering nitrate concentrations. One short term solution is simply to dilute the contaminated water with clean water and in this way lower nitrate contents. But if high inflows of nitrate continue from many localised sources, distributed over large areas, occasional dilution does not solve the problem in the long term. It is also important to remember that once high nitrate concentrations have built up in groundwater, it is more or less impossible to lower these quickly, even if the inflows of nitrate are reduced or completely eliminated.

Sewage effluent for irrigation of crops

Densely populated areas in many developing countries produce enormous volumes of sewage. There is an increasing shortage of good water for human consumption, and the same applies to water for food production. Attention has therefore focused on the reuse of sewage effluent. This must be taken into account when strategies are drawn up for the protection of groundwater, since sewage effluent has the potential to exert a highly negative effect on groundwater. On the other hand, the use of effluent on arable land may help return large quantities of plant nutrients into food production. A city with half a million inhabitants can in actual fact supply 6000 hectares of arable land with sufficient nitrogen and can also satisfy most of the phosphorus and potassium requirement.

A city with half a million inhabitants can in actual fact supply 6000 hectares of arable land with sufficient nitrogen and can also satisfy most of the phosphorus and potassium requirement.

In Mexico it is very usual for untreated sewage effluent to be used for irrigation, especially on land near the towns where the sewage is produced and where groundwater is often abstracted for drinking water. It is only relatively recently that attention has been given to the protection of groundwater in these areas. Solutions that are being discussed today are to collect the sewage in ponds where it is diluted with clean surface water before irrigation. If shallow groundwater has already been contaminated, it can also be pumped up and used to irrigate agricultural land, thus protecting the deeper groundwater that is needed for human consumption. Obviously, it is necessary to establish protection zones around drinking water wellpoints, in which the application of sewage effluent is prohibited, in order to prevent direct penetration of contaminated water.

Avoid the mistakes which we have made in the industrialised countries!

Avoid the mistakes which we have made in the industrialised countries! This is good advice to developing countries regarding the future protection of groundwater from nutrient contamination. This applies irrespective of whether the nutrients come from agriculture, inadequate sanitary facilities or sewage effluent that is used for irrigation.

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Groundwater and deforestation – do we need the trees?

Professor Anders Malmer, Department of Forest Ecology, Swedish University of Agricultural Sciences.

Groundwater recharge is often reduced due to soil degradation in deforested areas with dry seasons. However, to regain effective groundwater recharge by forestation of formerly deforested soils is not a straightforward matter. Scientific support for "payment for environmental services schemes" is weak, and it may be tempting to discard the need for trees in the landscape in favour of other land uses. Understanding of the fundamental function of landscapes in modern land use is urgently needed.

Trees have a role to play in most landscapes (Ethiopia). Photo: Anders Malmer.

Talking with farmers in tropical regions under deforestation, one often meets testimony or general perceptions that after deforestation there is less water in wells and in streams during the dry periods. This was for a long time debated as a paradox, because in general deforestation leads to increased runoff. In most cases, the lost transpiration and interception of former forests overrides the increased evapotranspiration from soil and lower vegetation. Not too long ago this debate was still heated and surrounded by uncertainty, as there was still little evidence from the tropics, only an understanding of most of the processes from humid northern hemisphere watershed studies.

Are forests sponges?

The hypothesis put forward for the decreased groundwater levels was that deforestation often leads to degradation of soils in terms of organic material, causing loss of infiltration capacity. Hence, a higher proportion of rainfall drains away faster in the form of surface runoff rather than infiltrate into the soil to restore groundwater levels for the dry season. This perception has been called "The forest sponge theory", an allegory that the forest retains water in the hills like a sponge. The term "desertification" was also partly related to this debate. Everyone who has experienced the contrast between the hotter air and dry surface soils of a deforested hillside and the contrasting cooler air and more moist ground in a nearby forest can perceive the fear of this "desertification". This terminology also related to a fear that deforestation would also reduce rainfall in the regions concerned. Terms like "from green hell to red deserts" appeared in scientific and policy debate.

Today research has produced more evidence for the effect of reduced dry season streamflows (and less groundwater) in seasonally dry areas. However, it still remains difficult to prove for larger basins with mosaics of many land uses, even when substantial deforestation is part of the changes. One reason for this, of course, is that converting forest to other land use does not have to lead to soil degradation per se. Good land management can play a role.

Reduced rainfall in deforested areas?

Physically, lower evapotranspiration and aerodynamic roughness in deforested landscapes give rise to lower atmospheric humidity and moisture convergence and thereby reduced cloud formation and rainfall. Attempts to build physical models of such possible reduction in rainfall have been made over several decades. Initially, crude physically based models for larger regions gave alarming indications. However, as models were refined the effect on the reduction of rainfall, for example by complete deforestation of the Amazon, was reduced to below 10%. Today, models are successively better, especially as the parametrization of real landscapes and land uses is improved. The relatively low modelled effect of deforestation on rainfall is associated with the strong impact of sea surface temperature, which in recent years has been understood to override the effects of land surfaces in most tropical regions apart from their most continental parts.

To add to modelling, trend analysis of long term records of rainfall is used to relate to trends of deforestation. These studies are gathering more evidence for significant reductions in rainfall correlating to deforestation in regions of Asia and West Africa. However the value of this evidence varies as to the strength of the relation between deforestation and rainfall and the way account is taken of high long term variation and periodicity in climate. For several cases, like West Africa, the correlation between annual rainfall and land characteristics (albedo) is weak, but improved when using longer time units like decades. This indicates that feedbacks between degrading or improving vegetation cover and rainfall are slow as vegetation trends do not switch between years but are slow processes.

High nitrate levels after fire

The bulk of studies on groundwater quality in forested areas and in areas under deforestation in the tropics focus on plant nutrients for understanding of forest ecology and effects of logging and other human disturbances. From this literature it can be concluded that it is not deforestation alone that may lead to harmful effects on groundwater quality, especially after fire. Reported nitrate levels at level above the 10 mg/l. WHO recommended maximum level for potable water may, for example, cause digestive problems for small children already at these low levels. This may be an emerging problem as fire is becoming more frequent in more fire-prone non-forest vegetations and secondary forests.

An additional emerging source for nitrate in groundwater may be the increasing need for fertilizers in intensifying shifting and permanent cultivation following deforestation. However, there are few, if any, specific studies or monitoring programmes for this problem in upland deforested areas in the tropics. On the pollutant side, as an indirect effect of deforestation, with less organic matter in soils, metals and heavy metals from pollution may be less easily bound in soil by organic complexation, and hence more mobile in groundwater.

No proof that forestation restores groundwater levels

There are a number of unknowns and constraints that contribute to current failures and/or lack of proved success in making the "return of forest sponge process" happen.

There is still no single scientific study in the tropics to prove that forestation restores dry season flows and groundwater levels. This fact has given rise to continued debate on "the forest sponge hypothesis" in recent years. Especially the policy of achieving soil and groundwater rehabilitation by extensive tree plantation schemes has been questioned. From the perspective of poor farmers' livelihoods, in contrast to forest conservation and forestation for water conservation, or payment schemes for environmental services, this may be a very important issue.

There are a number of unknowns and constraints that contribute to current failures and/or lack of proved success in making the "return of forest sponge process" happen. One constraint brought forward is that the increase in water use by new trees overrides the effect of increased groundwater recharge by improving soil quality. Both exotic tree species (most often used in plantation forestry) and indigenous pioneer species in secondary forests often reach the water use of former old growth forest in just a few years, while soil hydraulic properties on severely disturbed and degraded soils can take several decades to be restored, unless soil is actively scarified and enriched with organic material etc. Other factors complicating restoration of groundwater recharge can be heavy erosion which reduces soil depth and storage capacities, and increased water use in modern landscapes with mosaics of different land uses and types of vegetation. Factors that may contribute to the latter are extra heat (energy) advected from nearby bare patches and increased turbulence of winds which reduces humidity.

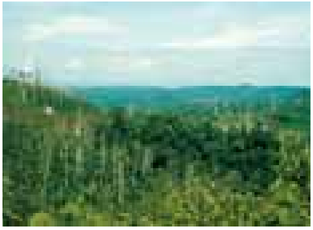
An important note regarding the issue of forestation and groundwater is that most research studies of (re)forestation pertain to cases of regeneration after recent deforestation by logging and shifting cultivation, while there are virtually no studies of forestation of seriously degraded lands. It must also be stressed that in some regions where water use by forest plantations contributes to problems of groundwater supply there are cases of afforestation in areas which do not support forests as natural vegetation, eg. in South Africa, Southern India and Fiji.

So why should we continue to promote tree planting?

There are two sides to the groundwater problem in areas under deforestation. The most important is lowered delivery of soil organic matter and maintenance of infiltration capacity.

The other side is the increased water use by young trees and young forests, possibly enhanced in open landscapes. An often oversimplified discussion could benefit from differentiation of different processes of land use change and land use intensity.

Deforestation by intensifying land use. In many regions there is urgent need for former forest land for the production of food and other products to enhance the income level of poor people. In such areas, large scale forestation may be problematic, even if it is possible when not sanctioned by local people. What remain to be found are intensified land use systems that meet needs of soil quality maintenance, while keeping the total water use in the landscape at reasonable levels. As such, many agroforestry systems may fulfil these goals. As for water use, the trees will increase interception of water in tree crowns, but often reduce evaporation from soils, more so in sub humid systems where the groundwater and dry season flow issue is most pronounced.



The landscapes today are mosaics of deforested areas, forest of different ages and cultivation. (Malaysian Borneo) Photo: Anders Malmer

Deforestation in extensive land use. In other regions there is deforestation in areas where wildfire is a driving factor, eg. in less densely populated parts of Southeast Asia and the Amazon. Typically this deforestation is initiated by selective logging, not well maintained plantation schemes, intensified shifting cultivation and opening of pasture land. What is a common feature of these land uses is openness and vegetation that more easily dries out, giving way to more frequent fires. Cycles of large scale wild fires, often in connection with El Niño climate oscillations, today create landscapes consisting of a mosaic of grasslands and various stages of secondary woody species. Hence, these landscapes are dominated by degradation of soil quality and young and highly water-consuming secondary forests. In this kind of situation one could argue that planting or maintaining young forests might not make matters worse, while old growth and mature forests would improve the situation. As such this is a structural problem, where there is need to allow land management and time to achieve landscapes with higher contents of mature forests in strategic locations for fire protection, water and biodiversity conservation etc. However, as stated above, there is a severe lack of scientific knowledge of potential hydrologic development in truly deforested and degraded areas.

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It is soil degradation after deforestation that reduces groundwater recharge in dry seasons. (Ethiopia)
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“Harvested” rainwater recharges groundwater

Professor Ronny Berndtsson, Department of Water Resources Engineering, Lund University

In arid regions, there is not enough groundwater for people’s needs. Rain is often the only water that is available. In such cases it is all the more important to collect and store rainwater so that it can be used when it is needed. The Stockholm Water Prize 2005 was awarded to CSE in India for its work on the collection of rainwater. In other places, it rains so much that dams are built as protection against flooding, and also for hydraulic power and irrigation.

Up-end the teacup on the saucer and you have a clever way of collecting rainwater! This collection arrangement is in the desert state of Rajasthan in India. With a hectare of land and 100 mm rain, 1 million litres of rainwater can be harvested. Photograph: CSE

An unusually warm autumn day in August 1975 was to herald one of the worst downpours in history and a huge catastrophe in central China. In six hours, more than 80 cm of rain fell on the mountain villages in the Hongru catchment area. Taken over one day, more than one metre of rain fell over large areas. As early as the 1950s, there was heavy flooding in this area, and it was decided to construct two large dams and a series of smaller ones to protect the population against future floods. Two large dams, Banqiao and Shimantan, were built.

Banqiao was designed to cope with a rain that, statistically, only occurs once in a thousand years, i.e. rain of 53 cm that falls over a three-day period. Shimantan was to deal with rain that falls no more than once in 500 years, i.e. 48 cm over three days. But on this warm August day in 1975, there was 45 cm of rain in a single day! This exceeded previous records by 40 per cent. And the rain continued with unabated strength for the next two days.

Both dams were designed to cope with a total of ca 50 cm of rain over a three-day period. After the persistent rainfall, they were filled to the brim. When the rain continued, the water level overtopped the crest of the dam by 40 cm, and both dams collapsed just after midnight on 8 August. This collapse generated an avalanche of water that was 6 metres high and 12 km wide. This floodwave of over 13,000 m^3/s swept over villages and populated areas downstream and caused the collapse of 62 small dams. Unofficial figures talk of more than 300,000 fatalities. More than 11 million people were seriously affected by disease and the effects of the flood and the enormous material destruction.

Dams must be both full and empty

One of the basic problems with heavy falls of rain is that it is necessary both to provide protection against them, and to make use of their positive effects.

The above example shows how important it is to be able to cope with a downpour safely. In most cases, dams are built so that floods can be stored for later use, for instance for irrigation or hydraulic power. But heavy rains can cause other types of problem apart from flooding. Intensive rainfall erodes the soil and washes away sedimented contamination. Major rainfalls also represent the bulk of the available water in these places. One of the basic problems with heavy falls of rain is that it is necessary both to provide protection against them, and to make use of their positive effects as resources for hydraulic power, irrigation and as a natural feature of the environment in the form of wetlands and lakes. To some extent, these wishes are in conflict.

In order that there should be protection against flooding, there must be dams that are relatively empty until a sudden and unpredictable downpour occurs. But for irrigation and hydraulic power, the reservoir must be full so that the greatest amount of water may be utilised. The way we try to reconcile these conflicting interests is to study the probability of rainfalls of different magnitudes. The difficulty is that reasonably reliable observations of rain are only available for about the past one hundred years. For reasons of safety, dams must be able to cope with perhaps a rainfall that, statistically, occurs only once in a thousand or even ten thousand years. It is easy to realise how difficult this is and that it can go wrong, as in China. There are also additional uncertainties due to global climate changes which may alter the intensity and magnitude of rainfall. These are the issues that occupy water researchers all over the world.

Collection of groundwater

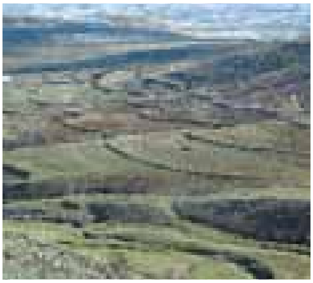
In arid and semi-arid regions, people depend on their ability to collect even the very small single rainfalls since they may represent most of the annual rainfall and the only available water resource in the area. The problem is how the water is to be collected and how it is to be stored. This is a problem which humanity has been facing over thousands of years in very arid regions.

In arid and semi-arid regions, people depend on their ability to collect even the very small single rainfalls.

One of the best known examples of collection methods is the khanat system that was developed in Iran about 3000 years ago. Khanats are hand dug tunnels which collect and conduct groundwater from rainy mountain areas through dry areas to towns and irrigation areas lower down. In Iran there are still about 300,000 km of these in existence, and they also still account for a large proportion of the existing water supply system.

Traditional methods in North Africa

The khanat method is based on water that has already penetrated or infiltrated down into the ground and formed capillary water and groundwater. But in this process there is a risk that a lot of the water vanishes through evaporation. Human inventiveness has found solutions even to this problem. There are archaeological indications that the first systems for the collection of rainwater were created about 9000 years ago in Jordan.



Terracing to collect rainwater and to counteract erosion in a wheat growing area in Tunisia. Photograph: Slah Nasri

In North Africa there are several traditional rainwater collection systems with different names depending on the local mean rainfall. Traditionally, these systems were based on communal management of the limited water resources and on social distribution depending on need and use. They went out of use in the first half of the twentieth century owing to large scale population movement into towns and industrialisation. European colonisation also contributed to the decline of this traditional knowledge. Small scale collection of water that was distributed locally was replaced by large scale centralised water administration which tried to deal with the water problems by constructing large dams based on European technology and European climatic conditions with a lot of rainfall.

In many cases, these large scale solutions caused serious environmental problems such as soil erosion, silting of reservoirs and salination of irrigation areas. Over the past decades, traditional systems developed for specific climatic types have therefore again been introduced. They are effective for storing small quantities of rain for the irrigation of different types of crops. In several places, these resuscitated methods have turned previous desert areas green and confounded researchers whose predictions of desertification have been proved wrong. Three of these methods are called Meskat, Jessour and Mgoud. Meskat is a micro-collection system specially developed to collect water for fruit trees during the rainy period. Jessour is terracing that collects water and eroded soil so that as little water and nutrients as possible are wasted. Mgoud is a specially developed system of canals which automatically lead water to the crops when it rains.

With this well, infiltrated rainwater can be used. Photograph: Slah Nasri

Old and new collection methods

But it is not only for crops that rainwater has been traditionally collected. The population in towns needed water for e.g. drinking and for the public baths. Large open paved areas such as squares and the forecourts of mosques were used for the collection of the sporadic rainfall which was stored in underground cisterns for later use. These collection systems can still be seen in the historic quarters of e.g. Tunis and Carthage. They are still often used, perhaps not for drinking but for laundry and as sanitary water.

In principle, traditional rainwater collection systems are found everywhere where people with unreliable access to water have lived. In the poorest, and also droughtiest, provinces of China in Gansu experiments are conducted on collection systems which are based on traditional techniques. Roofs, courtyards, paved roads and hillsides are used to collect the rainwater runoff into underground cisterns. The water is used both for drinking, general household purposes and irrigation.

Normally, rainwater is collected during the rainy period and is used during the long dry winter period. But storage of collected rainwater gives rise to problems with water quality. The water often contains bacteria and other types of contamination that can be present on roof surfaces and roads. Attempts are therefore made to develop local resource-saving methods that can clean the water. One technique is based on adding local red clay to the water. Particles in the water are adsorbed on the clay which can then be separated.

Rainwater collection in India

The Centre for Science and Environment (CSE) in New Delhi received the Stockholm Water Prize in 2005. This organisation has contributed to the renewal of traditional methods of collecting rainwater in the countryside and recharging groundwater reserves. They call this *rainwater harvesting*. They have shown that collection and storage of rain where only small quantities fall can be done with the help of the local population. In India there is a national network for the collection and management of rainwater (National Water Harvesters Network). CSE has been successful in ensuring that rainwater collection will become an accepted and important part of India's water strategy. This reinvigorated old technology that is now being put into practice reduces the pressure on India's ineffective and centralised system for the management of water, a system that partly derives from colonial times.

A partial solution to the global water problem?

The availability of water is a serious global problem today. Over the next twenty years the population of the world will increase from six to eight billion people. This will involve enormous water supply problems. About 70% of all the water is used to produce food. This proportion must increase by 50% in the next twenty years in order that sufficient food may be produced. A large proportion of this increase must presumably be provided by local collection and storage of rainwater and by local groundwater reservoirs.

For this reason, there is an urgent need to make a closer study of different systems for rainwater collection: how effective they are, how water quality changes during the period of storage, how the water can be re-used, and the chances of combining these with other technical solutions and irrigation methods. These are urgent research tasks which form the basis for sustainable utilisation of water.

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Forskningsrådet för miljö, areella näringar och samhällsbyggande, Formas
The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning

Box 1206, SE–111 82 Stockholm, Sweden. Visitors: Birger Jarls torg 5
Phone: +46 (0)8 775 40 00, Fax: +46 (0)8 775 40 10
E-mail: info@formas.se, www.formas.se