Management of Aquifer Recharge and Subsurface Storage

Making Better Use of Our Largest Reservoir

Netherlands National Committee — International Association of Hydrogeologists (NNC-IAH)

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Management of Aquifer Recharge and Subsurface Storage

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Editors
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Seminar
Wageningen
18 - 19 December 2002

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- **UNESCO United Nations Educational, Sientific and Cultural Division**
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Cover: courtesy Albert Thiadens

Preface

Early 2001 the Netherlands National Committee of the International Association of Hydrogeologists (NNC-IAH) took the initiative to consult a group of prominent representatives from the Dutch hydrogeological community on the possibilities to emphasise the role of groundwater to battle today's world water crisis. This took place in the aftermath of the 2nd World Water Forum (WWF) held in The Hague in 2000, and the previous conference of NNC-IAH in September 2000 titled: 'Evaluation and Protection of Groundwater Resources, From Vision to Action'. The Forum-discussion at the end of the NNC-IAH conference concluded that 'groundwater' should receive more prominent attention at the 3rd WWF in 2003 in Kyoto, Japan, than was the case at the 2nd WWF.

As a result from the discussions with representatives from the Dutch hydrogeological community, the NNC-IAH decided to focus its activities in 2001 - 2003 on Management of Aquifer Recharge and Subsurface Storage (MAR-SSS). MAR-SSS is considered a promising option for the improvement of sustainable and integrated water resources management. When climate variability was selected as one of the central themes for the 3rd WWF in Kyoto, NNC-IAH decided to emphasise the importance of subsurface storage as a strategy to cope with increasing needs for storage due to climate change.

In the framework of these activities, NNC-IAH and the Netherlands Hydrogeological Society (NHV) organised a conference on 'Recharge Enhancement and Subsurface Water Storage' held on 18 December 2002 in Wageningen, The Netherlands, followed by a seminar on 19 December in Heemstede and Amsterdam. It's objective was to share our Netherlands' MAR-SSS experience with that of internationally recognised experts from countries where MAR-SSS plays a relevant role in achieving sustainable water use and management. NNC-IAH invited experts from the following countries to present and discuss their country's status reports on MAR-SSS application:

- Hungary, Dr Zoltan Simonffy (University of Budapest) on induced bank infiltration;
- India, Dr Devinder K. Chadha (former chairman of the National Groundwater Board) on village level schemes;
- Kenya, Mr. Sam Mutiso (chairman SASOL) on subsurface dams;
- Mexico, Ing. Rubén Chávez Guillen (head, Groundwater Division, National Water Commission) on artificial recharge through well injection;
- Oman, Mr Saif Al-Shaqsi (former director Water Resources - Ministry of Water Resources) on recharge dams (Could not attend the seminar);
- South Africa, Gideon Tredoux (SCIR) on recharge dams and infiltration ponds.

Technical as well as financial support was given by the following international organisations:

- UNESCO - Working Group on Aquifer Recharge;
- GW-Mate, Bank Netherlands Water Partnership (BNWP);

– International Secretariat of the Dialogue on Water and Climate for the 3rd World Water Form (DWC-WWF-3); and
– IAH Commission on Management of Aquifer Recharge (IAH-MAR).

The booklet before you contains the proceedings of the conference of 18 December 2002 and the conclusions and recommendations of both conference and seminar on 19 December as submitted to the International Secretariat of the Dialogue on Water and Climate.

Other publications in this series of proceedings are:
1. Netherlands Hydrogeological Research in International Co-operation (March 1994).
2. Netherlands Experiences with Integrated Water Management, consideration for International Co-operation (October 1995).
3. Evaluation and protection of groundwater resources, from vision to action (September 2000).

Copies are still available with the secretary of the Netherlands National Committee for IAH.

Albert Tuinhof (Chairman NNC-IAH)
Jan Pieter Heederik (Secretary/treasurer NNC-IAH)

Amsterdam/Utrecht, 1 September 2003

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1 Making better use of our largest reservoir

Author Dr Stephen Foster

The most distinctive feature of groundwater systems is their relatively large – and sometimes positively huge – water storage capacity. The magnitude of this, of course, varies with geological build (Figure 1), but is always such as to make them the 'planet's largest freshwater reservoirs' with far more storage capacity than all man-made surface reservoirs. This subsurface storage capacity includes not only groundwater already stored in aquifer systems but also the potential of their void space (and elastic storage) to receive recharge, in part as a result of dewatering during intensive pumping. The more widespread, and socially-sustainable, use of groundwater storage to combat water-demand variability resulting from persistent drought and climatic change (on a scale of months to decades and beyond) is urgently needed.

The dialogue, however, should not be simply 'subsurface storage' versus 'surface dams', because in most cases optimal deployment of the latter is greatly facilitated by increased use of the former. Therefore, conjunctive use opportunities need to be much more systematically and vigorously pursued. World-wide, conjunctive use (even where practised) tends to have arisen more by accident than design, and aquifer storage remains the most neglected element of the hydrological cycle by practising water resource managers.

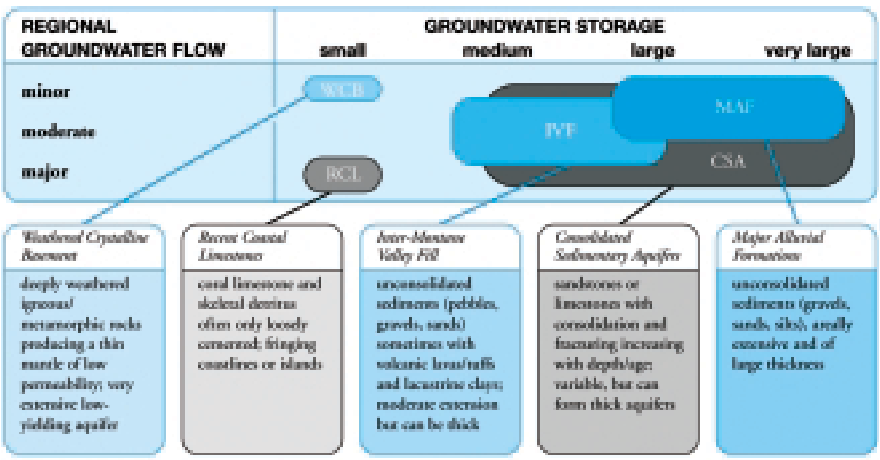


Figure 1. Summary of key properties of the most widely-occurring aquifer types giving a general qualitative indication of the wide range of natural groundwater storage capacity of different aquifer systems.

Groundwater recharge enhancement (including techniques of 'water harvesting' and 'artificial recharge') is another subject which until recently was much more talked about than practised. However, it is a matter of common observation that 'gravity irrigation on agricultural soils' and 'urban mains leakage and in-situ wastewater disposal' both usually result in large volumes of accidental groundwater recharge. If such unplanned activities on permeable soil profiles can result in very high rates of deep infiltration (Figure 2) then it should be feasible to achieve similar outcomes on a planned basis – using relatively low-cost techniques, ranging from improved rural land management to engineered basin recharge systems for urban water-supply.

It will, however, always be necessary to address certain basic considerations:
– the institutional issues relating to recharge enhancement, in terms of raising investment (who pays?), groundwater use priorities (who benefits?) and management arrangements (who controls ?);
– significant constraints on upstream recharge enhancement in hydrologically-closed basins, to avoid the diminution of downstream water availability;
– that supply-side interventions may be less cost-effective than measures to reduce water demand, and in reality both will be needed to stabilise the groundwater balance situation in the more arid regions;
– acceptable levels of drawdown of aquifer water-levels during storage exploitation, to protect groundwater level-related services (such as wetland conservation and supply accessibility via shallow waterwells)

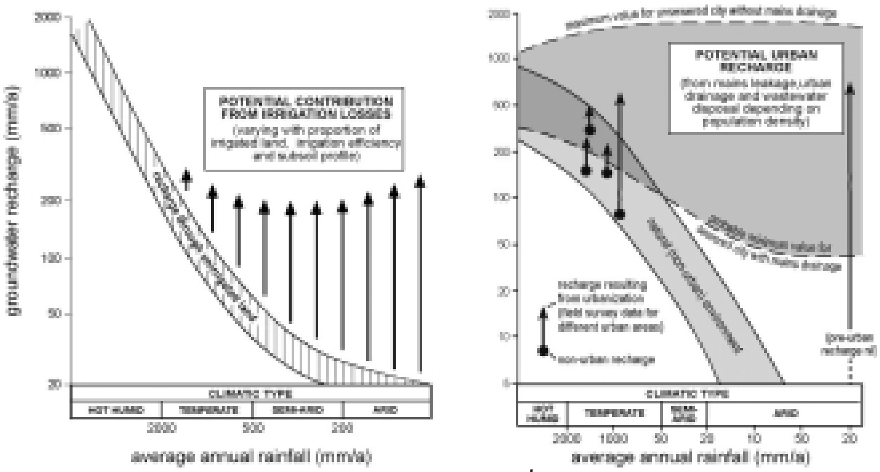


Figure 2. General scheme of variation of groundwater recharge rates under (a) irrigated agriculture and (b) urbanisation assumes presence of unconfined aquifer; effects of increased recharge will be more apparent when imported surface water is primary source of irrigation and urban supply.

But regardless of these concerns, the increased and improved manipulation of subsurface storage, when coupled with successful deployment of techniques to enhance deep infiltration and aquifer recharge rates, should allow increased long-term average rates of groundwater abstraction, which will benefit a wide range of users. Moreover, greater consideration needs to be given to the use of wastewater (the only global resource steadily increasing in availability) for aquifer recharge – this will involve endeavouring to maximise the resource benefits of wastewater recharge while minimising the pollution hazard for potable groundwater supplies.

2 Management of aquifer recharge and subsurface storage
A promising option to cope with increasing storage needs

Authors: Albert Tuinhof, Theo Olsthoorn, Jan Piet Heederik and Jacobus de Vries

1 Introduction

Provision of sufficient storage capacity under growing water demand and increasing climate variability is one the main concerns for water managers in the coming decades. Accurate estimates for the required storage capacity do not exist, but it is expected that in 5 - 10 years from now a multiple of the present storage capacity will be needed to provide sufficient water during dry periods.

Surface water storage in reservoirs behind (large and small) dams represents the major part of the installed global storage capacity. However, the recognition of the environmental and social impacts, the growing concerns about dam safety issues and increased sedimentation has clearly demonstrated the limitations of large dams. In contrast to the large increase in dam capacity over last 50 years, there has been no significant increase in the controlled use of aquifers for subsurface water storage. Also, it is not well known what the potential capacity of subsurface storage is. Yet, a debate on the limitations of large dams would make more sense if there exists a serious alternative to cope with the increase in storage capacity needed in the coming years to maintain even minimum supply levels to millions of people, both in rural and urban areas.

Subsurface storage is strongly linked to the infiltration of water into the aquifers (aquifer recharge). We will, therefore, refer to the whole process as Management of Aquifer Recharge and Subsurface Storage (MAR-SSS). This paper describes the concept and application of MAR-SSS and addresses the current role of MAR-SSS in providing water for agriculture and households. The last section addresses the potential role of MAR-SSS in meeting the growing storage needs in the coming decades under growing water demands and discusses its relationship with changes in climate variability.

Throughout the paper we have made valuable use of the report of the International Water Management Institute (IWMI) entitled 'Water Scarcity and the Role of Storage in Development' (IWMI, 2000).

2 Storage: concept and function

Storage and water demand

Water supply management is concerned with matching the supply of available resources with fluctuating demands of the different water-user groups. This matching occurs in *place* and *time*. Matching supply and demand in *place* refers to the conveyance and distribution dimension of water management, including pipelines, canals and pumping stations.

Matching supply and demand in *time* is dealing with storage. Storage is required to balance fluctuations in demand with availability of supply that is needed at different levels. The flushing reservoirs of toilets are an example of mini storage at household level. Other examples are roof tanks for overnight water storage and water storage tanks in rural and urban water supply systems (to balance daily demand fluctuations), both well-known landmarks in many urban areas. Large dams and artificial lakes store large amounts of water for balancing the inter-annual differences between river flows and water demands for domestic water supply and irrigation. In economic terms, the overall purpose of water storage can be expressed as: 'to capture water where and when the value is low and to reallocate water where and when its marginal value is high' (IWMI, 1998).

Storage and floods

A different function of storage, which is not further discussed in this paper, is when (river) water is discharged in excessive quantities and overflows embankments, causing floods as temporary storage of excess water. Floods are generally uncontrolled and are experienced as disasters, often causing large damage to people and environment. Otherwise, the use of retention areas may be a component in overall flood management. Storage in retention areas to regulate and control floods is a major issue in Western Europe where frequent floods in recent years have initiated a debate on the safety level of the existing dikes.

Storage and hydrological basins

Storage of water is part of the overall water management in a hydrological basin. With respect to the role and the impact of storage, different types of basins can be distinguished (IWMI, 1998):
- Open basins
- Closed basins
- Semi-closed basins.

Open basins have excess water above all committed requirements during the low flow season (Mazon River, Zaire River, and Yangtze River). This excess water is the unused outflow of river water to the sea, which has no opportunity cost and has zero marginal value. This water can be stored, but in general its marginal value will not significantly increase during the dry period.

In closed basins, there is no water reaching the sea (all year round) and every drop is used within the basin (Colorado, Yellow River, and Cauvery River). If water is stored (or used) by one user, it will go at the expense of another user. Water with low marginal value is restricted to the losses from non-productive evapo(transpi)ration from drainage or seepage.

In semi-closed basis, with excess outflow only during the wet season (Indus, Narmadi, and Ganges), there are major opportunities for adding value to water through storage. The excess water during the wet season (when it has a low marginal value) can be stored for use during the dry season when its value is potentially much higher.

Storage and climate change

The increasing need for storage is widely acknowledged and is the result of increasing water demands, changes in land use, runoff and the impact of changes in climate variability. It is not yet clear to what extent each of these factors contributes to the future storage needs at a certain location. Some regions will receive more rainfall as a result of changes in climate variability, but this may still lead to an increase in storage requirements if this rainfall comes in higher intensities and in shorter periods. Moreover, there may be a link between changes in rainfall and changes in land use and run-off, which will further influence the storage needs in place and time.

There is a need to investigate and predict the impacts of a changing climate and rainfall patterns on future storage requirements. We also need to assess the use of climate models for the design and operation of subsurface storage in general and subsurface storage systems in particular (Figure 1). This aspect will be further addressed in the last section of this paper.

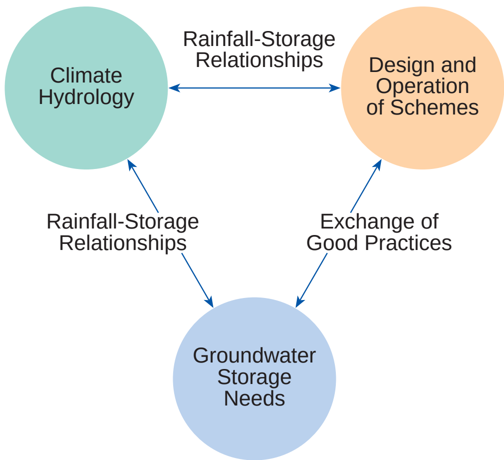


Figure 1. Elements of the dialogue on climate change and subsurface storage.

3 What types of storage do we distinguish?

Storage options

Generally, we can distinguish five ways of storing water:

- (rain) water storage in tanks for potable water supply and reservoirs for piped water-supply systems;
- water conservation in the soil profile (wetting of the soil during rainfall) or surface storage in depressions (e.g. rainfall-harvesting methods);
- subsurface storage on different scales (e.g. by artificial recharge);
- storage in small dams and reservoirs (often combined with induced infiltration to groundwater);
- storage in large dams and reservoirs.

The first two concern small-scale and/or short-term storage options. Rainwater storage may be for longer periods if the water is used only for drinking. The other three storage options usually cover longer periods (weeks, months, and years) and concern large quantities of water (millions or billions m^3). IWMI (2000) presents a useful comparison of the three major ways of storing water (Table 1).

Large dams and reservoirs

Large dams are usually defined as dams more than 15 meters high and with an embankment volume of more than 0.75 million m^3. Out of the 800,000 dams in the world (1997), 45,000 qualify as large dams with a total design storage capacity of some 6,000 km^3. The total withdrawal were estimated at 3,800 km^3

Table 1. Characteristics of subsurface storage: small dam storage and large dam reservoirs. (Source: IWMI Research Report no.39: Water Scarcity and the Role of Storage in Development)

	Subsurface storage	Small dams and surface reservoirs	Large dam reservoirs Large, reliable yield
Advantages	Little evaporation Widely distributed Operational efficiency Available on demand Water quality	Ease of operation Response to rainfall Multiple use Groundwater recharge	Carryover capacity Low cost per m^3 water stored Multi-purpose (power & flood control) Groundwater recharge
Limitations	Slow recharge rate Groundwater contamination Cost of extraction Recoverable fraction	High evaporation losses Relatively high unit cost Absence of over-year storage	Complexity of operation Siting High initial investment cost Time needed to plan & construct
Key issues	Declining water levels Rising water levels Management of access & use Groundwater salinization Groundwater pollution	Sedimentation Adequate design Dam safety Environmental impacts	Social impacts Environmental impacts Sedimentation Dam safety

(Gleick, 1998), or 60% of the design storage capacity. IWMI (2000) estimates that the present loss of storage due to sedimentation and lack of filling is probably 50% of the design storage or even more.

Although having the lowest cost per m^3, the limitations of large dams have become evident in the last decade due to increased sedimentation, acknowledgement of environmental and social impacts and dam safety questions (e.g. the vulnerability to earthquakes and floods).

In November 2000, the World Commission on Dams (WCD) completed a global survey of the performance, impacts and decision-making aspects of 125 large-dam projects – the *Cross Check Survey* (WCD, 1998-2001). The WCD concluded: ‘While there is great variability in the performance of the large dams contained in the Cross-Check Survey, the information indicates that the majority of dams in the survey under-performed with respect to the achievement of intended benefits and delivery of services. In some instances, benefits occurred for much longer periods than predicted in the studies and still continue. Adverse impacts on ecosystems occur frequently and a significant number of these adverse impacts are still unanticipated in the planning and decision-making’.

For the dams in the Cross-Check Survey that involve displacement of people, there was systematic underestimation of the number of families and people physically displaced and involuntarily resettled. The lack of enumeration of social records for reporting these aspects also remains a contested issue that continues to fuel controversy in the large-dam's debate.

The parameters for decision-making on dams have been changing over time. While there is a clear evidence of increased attention to social and environmental aspects in decision-making, technical, financial and economic activities still remain the most frequent overriding decisive factors.

Small dams and reservoirs

Small dams and reservoirs do have lesser restrictions with regard to impacts and safety, but the construction of small dams is hampered by the relatively high seepage and evaporation losses (up to 20% of the reservoir volume) leading to high unit cost compared to large dams and reservoirs.

Distinct advantages of small dams are the technological simplicity and ease of operation and maintenance, allowing for a strong community involvement. Many of the 750,000 small dams in the world have a dual purpose because of the groundwater recharge that is induced during storage. The recharge dams in arid countries, like Oman, have an important function in capturing floodwaters and enhancing the groundwater recharge from the erratic rainfall runoff.

Subsurface storage

Subsurface storage (or aquifer storage) has some important comparative advantages compared to surface water storage (Table 1). These advantages are related to the different nature of groundwater and surface water. Groundwater flows through aquifers (permeable geologic formations) from areas of recharge to areas of discharge with flow rates from less than 1 meter per year to several hundred meters per year. Tens, hundreds or even thousands of years may elapse between recharge and eventual discharge into a river, canal, spring or the sea. The low flow rates and the interaction with the surrounding rocks make the dynamics and processes in groundwater distinctly different from surface water (Table 2).

The world's aquifers represent an immense reservoir in which 3 - 4 million km^3 of groundwater is stored (up to a depth of 400 meters). In contrast, the total storage of surface reservoirs, including fresh-water lakes, is in the order of 120 000 km^3. A more interesting figure is the effective natural storage of groundwater, which is determined by the annual groundwater fluctuation. Storage is used during dry periods when groundwater levels drop under continuing groundwater discharge and/or abstraction and is replenished through natural and/or artificial recharge during the subsequent period with excess rain. Assuming that 20% of the global land area is underlain by aquifers that are pumped during the dry season with an average seasonal groundwater level fluctuation of 1 meter, this natural storage capacity is in the order of 3,000 km^3 per year. This is about the same order of magnitude as the actual annual withdrawal from all major dams on earth.

Table 2. Comparative advantages of groundwater and surface water. (Modified after Llamas, 1998)

	Characteristic	Groundwater resources and aquifers	Surface water sources and reservoirs
Hydrogeological	Storage volumes	Very large	Small to moderate
	Resource areas	Relatively unrestricted	Restricted to water courses and canals
	Flow velocities	Very low	Moderate to high
	Residence times	Generally decades/ centuries	Mainly weeks/months
	Drought propensity	Generally low	Generally high
	Evaporation losses	Low and localised	High for reservoirs
	Resource evaluation	High cost, significant uncertainty	Lower cost with generally less uncertainty
	Abstraction impacts	Delayed and dispersed	Immediate
	Natural quality	Generally high (not always)	Very variable
	Pollution vulnerability	Variable natural protection	Largely unprotected
	Pollution persistence	Often extreme	Mainly transitory
Socio-economic issues	Public perception	Mythical, unpredictable	Aesthetic, predictable
	Development cost	Generally modest	Often high
	Development risk	Less than often perceived	More than often assumed
	Style of development	Mixed public and private	Largely public

4 What do we mean with aquifer recharge?

Definitions and terms

Aquifer recharge and change in subsurface storage include the result of the natural groundwater recharge-discharge regime and artificially managed processes. Thus subsurface storage is induced by any recharge, either natural or artificial. Table 3 gives an overview of recharge types and related storage/retrieval options.

Natural aquifer recharge

Aquifer recharge normally fluctuates in response to seasonal and long-term climatic effects. The reaction of the aquifer's discharge to a change in recharge is an increase or decrease in the hydraulic gradient through a change in groundwater head, which in turn results in a change in groundwater storage. Thus, a groundwater system is self-organising with change in storage as regulator. Change of storage not only occurs in the saturated zone by a changing groundwater level; the unsaturated zone also shows a fluctuation in soil moisture content and an associated change in the moisture pressure gradient. Moisture content and pressure gradient together control and regulate the percolation flux.

Table 3. Types of groundwater recharge.

Recharge	Storage and retrieval	Example
Natural recharge	Unmanaged, but with limited groundwater abstraction compared to natural recharge and without stress on the resource	Groundwater use in the Terai region in Nepal
	Unmanaged but with increased groundwater abstraction and increased stress on the resource	India after introduction of small irrigation pumps
	Stress on the resource but groundwater management plan in place to control side effects	Intensively exploited aquifers in Europe and the US
Enhanced recharge and controlled use	In-situ enhancement of recharge with a managed recovery system	Recharge dams in Oman that intercept flash floods to increase recharge. Also bank infiltration belongs to this category
	Infiltration of imported water in conjunction with a managed recovery system	Dune filtration in the Netherlands, pond infiltration in USA, and ASR in Australia.
Incidental recharge	Unmanaged recharge as side effect of water resources development	Infiltration of excess irrigation water in irrigated areas and leakage from water mains and sewers

The groundwater discharge rate can, apart from the change in groundwater level/storage, be regulated, (1) by the number of drainage channels and seepage horizons that participate in the drainage process, and (2) by a change in evapotranspiration through a shift in the depth of the evapotranspiration front. These processes particularly play a role in shallow aquifer systems. Groundwater extraction normally reduces the natural groundwater flow discharge as well as the evapotranspiration.

Recharge enhancement

It is evident that recharge enhancement requires both storage space and infiltration capacity. The seasonally dependent groundwater table depth mainly controls the storage space under natural conditions and thus groundwater extraction creates an increase in available storage space. Infiltration capacity is mainly determined by the permeability-related properties of the soil. Whether the infiltrating water will eventually contribute to recharge depends largely on the retention storage and evapotranspiration. High retention storage in the root zone means that (part of) the infiltrated water subsequently can disappear by evapotranspiration. This process dominates especially under (semi-)arid conditions where potential evapotranspiration exceeds rainfall on a seasonal base. Thus, a sandy subsoil with a high infiltration capacity may largely prevent recharge, whereas fractured hard rock – notably exposed karst surfaces – may produce high recharge rates under the same climatic conditions, because the percolating water in the latter case may escape evapotranspiration, due to fast infiltration and poorly developed root systems.

Recharge enhancement means an artificial increase of recharge by increasing the supply of water from outside the groundwater basin (normally river or stream water) or by improving the infiltration capacity, so that more water from inside the basin will infiltrate at the expense of surface runoff and/or evaporation. Infiltration enhancement can be achieved by removing clayey material and crusted soil, water conservation measures in the soil, and by measures to accumulate water in depressions and behind obstructions. Net recharge can be increased by reducing transpiration through removal of vegetation, and by lowering the groundwater level by groundwater extraction from shallow aquifers.

A profound knowledge of all aspects and components of the groundwater system, including its dynamics, natural renewal rate and susceptibility to pollution, is a prerequisite for the development of a sustainable system of enhanced recharge and extraction. Evaluation of the groundwater basin's characteristics thus requires:
- knowledge of the hydrogeological properties of the subsurface by pumping-tests analysis, bore-log and geophysical interpretations and climate;
- understanding of the dynamics of the recharge-discharge-storage system by analysis of groundwater-level fluctuations;
- identification of the areas of recharge and discharge by geomorphologic mapping and remote sensing (earth-observation) techniques;
- detailed study of the recharge mechanisms and soil-water balance studies.

Incidental recharge

Incidental recharge refers to induced infiltration as a side effect of irrigation, surface storage, leaking water supply and sewerage systems. The term 'incidental recharge' is used in case this infiltration is not included in the water management system and occurs as unplanned side effect.

5 Management of aquifer recharge and subsurface storage

Type of aquifer storage schemes

Aquifer recharge and subsurface storage is a known technology that for hundreds of years has already been applied successfully in many countries. Classical examples of harvesting systems (such as storage tanks, dams, terracing and runoff diversions) are known in many regions particularly in arid en semi-arid zones. The water-harvesting systems in the Middle East are a good example of a water-conservation technology that has developed over the last 6000 years. Although many of the ancient systems have been abandoned due to poor maintenance and changing socio-economic conditions, there is a renewed interest in traditional systems and to revive them through the use of new technologies. The large number of recharge dams and other aquifer-recharge-enhancement structures provide a good insight in the importance of groundwater harvesting in the Middle-East region. A good overview of ancient and modern harvesting technologies is provided in the UNESCO/ROSTAS state of the art report on Rainfall Water Management in the Arab Region (ALSAD, 1995).

Recharge dams to store the flash floods in wadis and to increase of the infiltration into the aquifer are a good example of MAR-SSS. Worldwide, there is wide variety of MAR-SSS schemes on different scales and for different purposes. Systems of the same type are found in various countries under different names and of site-specific or region-specific designs. Table 4 gives a proposed classification of the MAR-SSS systems. From the countries underlined, state of the art country reports are presented in the following contributions, as presented during the NNC-IAH conference on 18 December at Wageningen, The Netherlands.

Table 4. Proposed classification of MAR-SSS systems.

MAR-SSS technique	Names used	Country examples
1. Village level gravity injection	Dug wells, recharge shafts, village tanks trenches, gravity injection wells	China, India, Thailand
2. In-channel structures	Gabions, percolation tanks (India), subsurface dams, sand-river dams, recharge dams	Egypt, India, Kenya, Namibia, Oman
3. Off-channel infiltration ponds	Large basins sometimes supplemented with injection devices	Egypt, the Netherlands, Taiwan, South Africa
4. Pressure injection	Injection wells and injection-recovery wells, so called Aquifer storage recovery wells (ASR wells)	Australia, Mexico, USA
5. Induced bank infiltration	Sometimes supplemented with injection devices impacts	Germany, Hungary

In the following boxes some typical examples are presented on the state of the art of the MAR-SSS techniques in three different countries: gravity injection in India (Box 1), ASR applications in the USA (Box 2) and rainwater injection from glass houses in the Netherlands (Box 3).

Box 1. Gravity injection in India

In the state of Harwana, northern India, simple wells are used, which consist of a borehole through covering clays into an underlying sand aquifer (up to 50 m deep). Instead of using a screen, a semi-spherical space of 1-2 m diameter is washed out immediately below the overlaying clay layer. To prevent collapse of the cavity, the so-called cavity type wells have a maximum capacity of up to 30 l/s. Because the groundwater tends to be brackish, these wells have been retrofitted to inject harvested rain or excess canal water whenever available. This results in a much larger fresh-water availability from these wells in the months following the rain period, with over 60% recovery of the injected volume. Despite high suspended loads in the injection water (up to 900 mg/l) and injection rates exceeding the extraction rates, no operational problems due to clogging are experienced with these particular wells. This probably is due to easy removal of suspended solids from the open hole during extraction of the apparently initially turbid water (>2,000 mg/l suspended matter). The benefit in terms of money outweighs the cost of retrofitting by a factor of 25 or more, amongst others because of the shift to higher valued crops, thanks to the availability of more fresh water during the growing season (Malik et al, 2002).

Box 2. ASR applications in the USA

Artificial Storage Recharge wells are specially designed -wells, suitable for (very) high injection rates for storage and 'at demand' production for recovery of the stored water. ASR can be used for storage of water on different time scales, of which seasonal storage may be the most important. By subsurface storage of surface water runoff during the winter, ARS can serve to bridge summer drought and other dry spells when abstraction of surface water is restricted by regulations. The preconditions are a limited loss of water over the storage season and limited quality changes of the surface water during storage to prevent treatment requirement of recovered water. ASR wells can be used on short time scales to bridge demand fluctuation. Here the cost of the ASR should be less than that of the extra treatment requirements to comply with peak demands from surface water. Sometimes ASR serves to have fresh water available under emergencies such as hurricanes on subtropical islands. To this end, locality and protection is more important than losses during storage. In this particular application, contrary to application in which this is not economically feasible, continuous injection at a small rate in a saline limestone aquifer may be acceptable. ASR bears many options for solutions under specific conditions, which have to be investigated and evaluated carefully.

A not fully acknowledged collateral benefit of ASR is the automatic back washing of the wells during the extraction period, resulting in a prolonged lifetime of the wells. In those cases where the groundwater extraction exceeds the injected volume, oxidation of grain adsorbed iron and manganese may lead to the removal of iron and often also of manganese. This natural subsurface treatment can be a substantial extra 'cost benefit' of ASR. In general, the recovery of ASR can be high and it increases during the first couple of storage recovery cycles, to almost 100% under favourable conditions. To deal with this from the 'cost benefit' point of view, David Pyne (oral discussion during Second Int. Symp. On Artificial Recharge, Amsterdam, 1998) introduced the interesting concept of 'Target Storage Volume'. This is the minimum volume required to cover the subsequent demand including the volume necessary to compensate for losses due to natural drift of groundwater, density effects and mixing. It guarantees 100% efficiency from the operational point of view, while the extra injection volume needed is included in the overall operational cost together with pump maintenance etc.

In the USA ASR wells gain more and more popularity, thanks to the inspiring promotional efforts of David Pyne (1995). More than 56 ASR well fields are now operating in the USA (Pyne, 2002). This work also leads to more and more ASR well applications outside the USA.

Source: Pyne (1995, 1998 and 2002) and oral communication Olsthoorn – Pyne on several occasions (1995 - 2003).

Box 3. Rainwater injection from glasshouses in the Netherlands

In the low-lying western part of the Netherlands, glass-house vegetables and flowers need very fresh irrigation water of <50 mg Cl^-/l. Because surface water is too saline and groundwater is brackish, ASR wells are used to inject rainwater, collected from their glass houses roofs, into the aquifer between 15 and 50 m depth. Since about 1983 over a hundred installations have been built, which in general operate successfully where the groundwater salinity is limited to about 1000 mg Cl^-/l and its velocity is less than about 10 m/year (Olsthoorn, oral information from local users, 1983 - 86, 2003).

Composite recharge and storage; surface water and groundwater

Surface water and groundwater are part of the hydrological cycle and in continuous interaction. In many water management systems, a combined use of groundwater and surface water is applied. When combined use of groundwater and surface water is part of the water-management strategy, the term 'conjunctive use' is often applied. The term means that groundwater and surface water are used in tandem, taking into account (and making use of) the comparative advantages of both resources. Examples of such schemes are:

– (excess) surface water is used for irrigation in the wet periods and groundwater is pumped in dry periods to supplement or replace the surface water supply;
– storage dams create surface-water storage but also retard the run-off and enhance groundwater recharge. The groundwater recharge may be further enhanced by conveying water from the (temporary) surface water reservoir to infiltration facilities (Omdel dam in Namibia);
– off channel infiltration ponds are usually recharged with river water for storage purposes and for water quality improvement (The Netherlands);
– induced bank infiltration is an example where infiltrated river water is pumped as groundwater;
– storage reservoirs used as irrigation tanks are being converted into recharge ponds (India).

Also, in design and operation of storage structures there are complementarities. These apply for storage reservoirs where operational efficiency can be improved by combining one or more large reservoirs with a large number of smaller reservoirs ('tanks') within one river system.

The above examples underline the principle that water conservation is not a purpose in itself but that the objective is to aim at an operational optimum, in order to have the water available *where* and *when* it is needed.

Inventory of present storage capacity

In the fall of 2002 the Management of Aquifers Recharge (MAR) Commission of the IAH has started a worldwide inventory of MAR-SSS schemes. Based on the above classification (Table 4), an inventory sheet was composed that summarises some key figures on country level or on regional/state level for those countries with a wide application of MAR-SSS (for example India and the USA). Twenty countries have so far responded to the first distribution round. Based on this information some tentative results can be presented:

– national capacities varies widely form 1 - 1,000 million m^3/year;
– the number of schemes per country ranges from 1 - 20. Two countries have more than 100 schemes;
– a wide variety of techniques is applied, all 5 categories in Table 4 could be identified;
– most schemes are installed for drinking water supply: to ensure good quality water and to provide water during dry periods.

Subsurface Storage and climate variability

The imbalance between water supply and water demand in time, and to a lesser extent in space, is for an important part associated with climatic variability and seasonallity in rainfall and evapotranspiration. The need for storage, apart from other factors, thus largely depends on climate. Therefore, a regional differentiation of storage requirements is closely connected to the regional distribution of climatic zones with their characteristic seasonal patterns of rainfall and evapotranspiration. A classification of the relevant climatic characteristics and associated storage requirements and storage capacity thus provide a framework for an evaluation of the influence of climatic change in this respect.

The climate classification according to Thornthwaite, which is based on the soil moisture balance, provides a suitable first assessment of the water balance and recharge (storage) potential as function of the climatic conditions and climate change. This method characterises the hydrological climate by the average annual water balance regime, based on rainfall and potential evapotranspiration E_p. The actual evapotranspiration E_a is estimated as function of E_p, soil moisture and vegetation for average soil conditions. Water surplus equals discharge by surface runoff and/or groundwater discharge; the latter in turn equals groundwater recharge. Figure 2 illustrates this method for a typical semi-humid regime and a typical semi-arid regime for average soil conditions.

This method is more suitable to characterise the potential hydroclimatic conditions than the actual water balance. The actual water balance, and particularly the groundwater recharge, is under any climate regime strongly dependent on the actual subsurface condition. In the first place this condition controls the maximum possible recharge by the infiltration capacity and storage capacity, and thus determines the amount of water that has to be discharged by runoff and/or stored at the surface. Secondly, the subsurface conditions determine the retention storage and associated evapotranspiration, and therefore the loss of subsurface water by evapotranspiration as well. For instance, the average groundwater recharge in the Kalahari semi-desert with a sandy subsurface and an annual rainfall of 450 mm is a few millimetres per year because of a high retention storage of soil water and subsequent evapotranspiration. In contrast, there is an example of a desert area in Saudi Arabia with an exposed karst surface and an annual rainfall of 200 mm, which produces a recharge in the order of 100 mm per year because rainwater can rapidly percolate and thus escapes evapotranspiration (De Vries and Simmers, 2002).

6 Storage needs in the coming decade

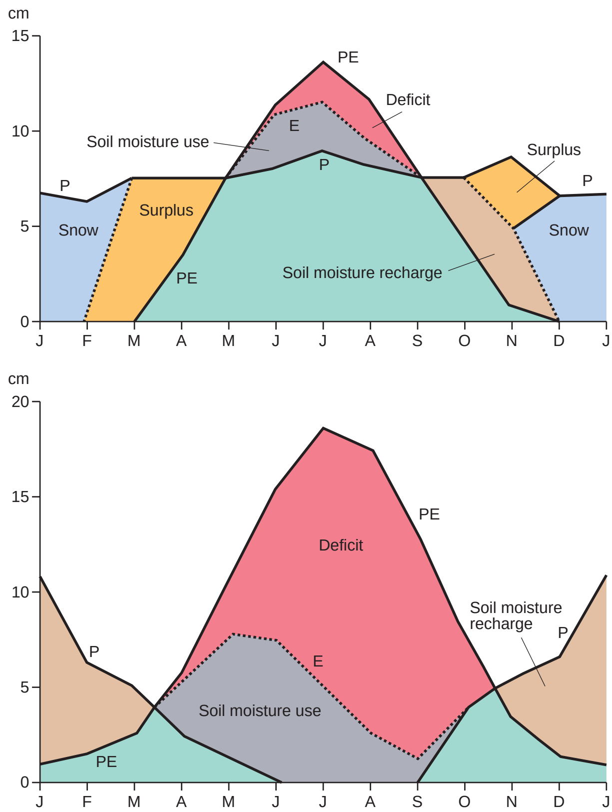


Figure 2. Moisture budget diagram for Concord, New Hampshire (semi-humid) and Aleppo, Syria (semi-arid). The surplus is discharged as surface runoff and/or as groundwater discharge; the latter equals groundwater recharge. (after Barry, 1969, based on data from Thorthwaite & Hare, 1965, and Mather, 1963).

Growing needs

The need for storage is steadily growing because of:

- increasing water demands due to growing population and increase per capita consumption;
- catchment degradation and erosion causing an increases of run-off from rainfall while base flows are concurrently decreased;
- changes in rainfall regime as a result of changes of climate variability, causing more profound floods and droughts.

Estimates for Kenya indicate that, due to population growth and climate variability, the total storage volume needed in 2010 will be 30 times the current storage volume. This figure may even double if the effects of catchment degradation are taken into account. These are alarming figures, especially for developing countries where investments in water infrastructure are already below needs and where the economic growth rates do not give hope for a substantial increase in the foreseeable future.

Globally, the World Water Vision presented during the 2nd WWF in The Hague (2000) estimated that an additional 150 km3 of storage would be required for irrigation by 2025 and another 200 km3 to replace the current over-consumption of groundwater. Moreover, the Statement of African Ministerial Conference on Water at the World Summit on Sustainable Development in Johannesburg in August 2002, recognised that the per capita water storage in Africa is about 1% of the per capita water storage capacity in Europe.

To plan for the required storage facilities (to calculate capacities and to determine locations) it is important to have more insight in the impact of the different aspects, such as: increasing demand, catchment degradation and (changes in) climate variability. The purpose of this paper is to initiate a dialogue on these issues and in particular on the impact of climate variability.

Impact of changes in climate variability

Climate change may alter the figures of worldwide and regional annual water balance components as well as their seasonal variation and regime. This affects the associated distribution of available water over surface runoff, subsurface discharge and storage. Weather and climate forecast are indispensable tools in developing a storage strategy. Climate change and its impact on storage and storage requirement can be exemplified and summarised by the following aspects:

- stronger seasonally with wetter and dryer periods require more storage capacity to overcome dry periods and to reduce floods;
- higher rainfall intensities may result in exceeding the infiltration or storage capacity and thus in higher floods. This requires the creation of storage, enhanced infiltration or artificial recharge;
- lower rainfall results in the need for transport and storage of water from other areas;
- changes in vegetation will cause changes in evapotranspiration, surface runoff, erosion and sediment transport/deposition. This asks for water- and soil-conservation measures, like terracing.

What is the impact of changes in rainfall pattern (due to climate change) on the need for storage and on the design and operation of recharge enhancement schemes? Linkage of climate information (statistical forecast on changes in rainfall patterns and results of climate models) with questions of groundwater managers will provide information on three main issues:

- How will the need for storage change under changing climate and rainfall patterns?
- To what extent will existing schemes be affected by climate variability and changes in rainfall?
- To what extent can climate classifications (such as from Thornthwaite), models and forecasts contribute to the planning, design and operation of managed aquifer recharge schemes?

Development options for subsurface storage

With the growing concerns about the impacts and safety of large dams, there is clear incentive to look into additional storage options such as subsurface storage and small-scale (but low cost) water-conservation methods. Future storage capacity will hence be a mixture of:

- large and small dams;
- groundwater recharge;
- traditional small scale water conservation techniques and rainwater harvesting;
- water storage in wetlands in combination with increasing water-use efficiency and water conservation.

The most important objective of storage is preventing losses of potential value: losses to the sea and other mixing with brackish and saline waters and losses by non-beneficial evaporation for instance in lower discharge areas. Storage has to be evaluated on a basin-wide scale, as upstream storage may cause less availability for downstream uses. In fact, storage for saving water, is only useful where otherwise non-beneficial losses can be reduced or prevented, that is in semi-closed basins, i.e. basins where otherwise peak or winter flows are lost. Storage for flood-control is a different matter, but both go often hand in hand.

It is anticipated that a substantial portion of the required storage capacity in 2025 (IWMI, 1998) has to be provided by groundwater (recharge) through the development of operational (technical and institutional) instruments for enhancement of controlled aquifer recharge, storage and subsequent recovery of the water when needed. These systems are needed on different scales (including community-based schemes) and will include countries with insufficient knowledge of the design and operation of projects to manage aquifer recharge. For example, in Taiwan where after the recent earthquakes the safety of dams is seriously questioned, a policy is being considered to replace surface water storage facilities by groundwater recharge schemes. Such schemes are a new phenomena for that country.

7 Concluding remarks

There is a large potential for subsurface storage, notably in areas with deep groundwater tables and no risks for collateral problems such as water logging. Next to storage in empty pore space in the unsaturated zone, fresh water may also be stored by replacing saline water, like in coastal aquifers and in many arid areas.

Subsurface storage requires surface retention or controlled transport to the recharge areas and subsequent retention storage to allow the infiltration to take place. One of the most promising and necessary ways to increase subsurface storage throughout the world in general, is proper and controlled land use to reduce and delay surface runoff as much as possible. Another benefit of upstream retention and delay is to prevent silting of reservoirs by reducing surface runoff and associated soil erosion. The 600-year-old Yemen terracing system is one of the most magnificent examples of this practice. Unfortunately, due to economic and demographic developments these terraces are rapidly eroded.

In general, recharge enhancement methods and storage options are so varied and site-specific that local potential and cost evaluation will always be necessary. Proper hydro(geo)logical as well as technical analysis and subsequent evaluation of the results are thus a prerequisite for success.

From several points of view, water harvesting and/or roof collection in cities, coupled with injection, are highly beneficial to compensate for the relative large turmac or non-infiltration area and the high groundwater abstraction under many cities. Related positive factors are the reduction of water nuisance in wet periods, as well as the overall wastewater volume and its infrastructure. This will reduce costs and improve public health in general.

Good practices should be exchanged on a worldwide basis. IAH-MAR commission on recharge enhancement technologies with its thematic subgroups forms a good entry for communication and experience exchange.

References

- ***ACSAD*** (1995): Rainfall Water Management in the Arab Region, State of the Art Report, ROSTAS, Cairo.
- ***Barry, R.G.***: Evaporation and transpiration, In: Chorley, R.J. (ed), Introduction to physical hydrology. Methmen, 1969. pp. 82 - 89.
- ***De Vries, J.J. & I. Simmers*** (2002): Groundwater recharge: an overview of processes and challenges, Hydrogeology Journal 10, pp. 5 - 17.
- ***Dillon*** (Ed) (2002): Management of Aquifer Recharge for Sustainability, Proceedings of the fourth International Symposium On Artificial Recharge, ISAR 4, Adelaide, 22 - 25 Sept. 2002.
- ***World Commission on Dams***, Large Dams Cross-Check Survey, Final Paper - Executive Summary, November 2000.
- ***Gleick, Peter H.*** (1998, Also: the new volume 2002 - 2003) The World's Water: The Biennial Report on Freshwater Resources, Island Press, Washington, D.C..
- ***Llamas***, 1998
- ***Malik, R.S., B.S.Jhohar, R.K.Jhohar, T.Streck & J.Richter*** (2002): Long-term successful operation of existing brackish cavity wells for ASR to improve quality for irrigation by Indian farmers, In Dillon (Ed) Management of Aquifer Recharge for Sustainability, Proceedings of the fourth International Symposium On Artificial Recharge, ISAR 4, Adelaide, 22 - 25 Sept. 2002, Balkema Publishers, ISBN 90-5809-527-4, pp. 465 - 467.
- ***Pyne, R.D.G.*** (1998): Aquifer Storage Recovery: Recent developments in the United States. In Peters, J.H. (Ed) Artificial Recharge of Groundwater. Proceedings Third International. Symposium. On Artificial Recharge of Groundwater – TISAR 98, Amsterdam 21 - 25 Sept. 1998, p 257 - 261. Balkema Publishers, Rotterdam, ISBN 90-5809-017-5, 474 pp.
- ***Pyne, R.D.G.*** (1995): Groundwater Recharge and Wells. A guide to Aquifer Storage Recovery. Lewis Publishers, Boca Raton etc., ISBN 1-56670-097-3, pp. 367.
- ***Pyne, R.D.G.*** (2002): Water Quality changes during aquifer storage recovery (ASR). In: Dillon (Ed) Management of Aquifer Recharge for Sustainability, Proceedings of the fourth International. Symposium. On Artificial Recharge, ISAR 4, Adelaide, 22 - 25 Sept. 2002, 65 - 68, Balkema Publishers, ISBN 90-5809-527-4.
- ***Seckler, Andrew, R. Sakthivadivel and David Seckler*** (?): Water Scarcity and the Role of Storage in Development, Research Report no 39,IWMI, Colombo.
- ***Shah, Tushaar, David Molden, R. Sakthivadivel and David Seckler***: The Global Groundwater Situation, IWMI, Colombo.

3 State of art of artificial recharge applied on village level schemes in India

Author Dr. Devinder K. Chadha

Abstract

The unregulated development of groundwater, particularly of hard rock aquifers in arid and semi-arid areas, has resulted in a continuous decline of water levels over an area of about 340,000 km2. Out of total annual precipitation of 4000×10^9 m^3 in India, about 1240×10^9 m^3 is annually lost as surface runoff. It has been estimated that 872×10^9 m^3 (bcm is further used for 10^9 m^3) water is still available for recharge and it is feasible to have subsurface storage of 214 bcm. As part of this total feasibility, India plans to have subsurface storage of 36 bcm by constructing about 230,000 small and simple recharge structures such as percolation tanks, check dams, subsurface dykes, etc. The present case study pertains to the over-exploited unconfined aquifer, wherein the average water has declined by 10.5 m since 1972. In this project a 295 m long trench with 30 vertical shafts 2 to 3 m in diameter have been constructed to store 4.79×10^9 m^3/year of the surplus monsoon water. The impact analysis showed considerable improvement in yield of the running tube wells, a rise in water level and the possibility to install 130 additional shallow tubewells.

1 Introduction

India's economy is based on agriculture. The development of groundwater resources became imperative as 174 bcm surface water storage fell short of the water requirements for different user sectors, particularly for agriculture. The uncontrolled development of groundwater through construction of 17 million open wells / shallow tubewells and subsequently by deep tubewells increased the irrigation potential from 6.5 mha during 1950 to 49.5×10^6 ha during 2002. This development met the major requirements of irrigation and drinking water requirements of 700 million rural population and more than 50% of the urban and industrial sectors, but also resulted in over-exploitation of aquifer systems in more than 10% of the country's area i.e. 0.34 million km^2. The increase in groundwater structures and the irrigation potential created during different periods is given in Table 1.

Table 1. Growth of groundwater structures and irrigation potential.

Year	Dug wells (×1000)	Private tube wells (×1000)	Public tube wells (×1000)	Total (×1000)	Cumulative irrigation potential created (10^6 ha)
March, 1951	3860	3	2.4	3865.4	6.5
March, 1980	7786	2132	33.3	9951.3	22.0
March, 1985	8742	3359	46.2	12147.2	27.82
March, 1990	9407	4754	63.6	14224.6	35.62
March, 1992	10120	5379	67.6	15566.6	38.89
March, 1997	10501	6743	90.0	17334.0	45.73
March, 2002	**NA**	**NA**	**NA**	**NA**	**49.50 (approx.)**

NA = Not available

2 Impact of groundwater development

The unregulated development of groundwater occurred particularly in the arid and semi-arid areas. Here the problems with over-draft and associated quality problems emerged. The number of over-exploited areas has continuously increased. In fact, the annual volume of groundwater pumped is more than is annually replenished. Hence, the areas where groundwater development exceeds 85% of annual replenishment, increased from 253 during the years 1984 - 85 to 445 in 1997 - 98. These so-called 'dark blocks', totalling an area of about 0.40 million sq. km, shows a continuous decline of the groundwater table. The number of over-exploited areas and 'dark blocks' increased from 253 during 1984-85 to 445 during 1997-98, the state wise information is given in Table 2.

Table 2. Status of over exploited and dark blocks.

State	Number of Dark Blocks		
	1984 - 1985	1992 - 1993	1997 - 1998
Andhra Pradesh	0	30	26
Bihar	14	1	11
Gujarat	6	26	28
Haryana	31	51	41
Karnataka	3	18	16
Madhya Pradesh	0	3	3
Punjab	64	70	83
Rajasthan	21	56	94
Tamil Nadu	61	97	103
U.P.	53	31	40
Total	**253**	**383**	**445**

It is anticipated that with this rate of development about 35% of the country's area will show over-exploitation by 2017.

3 Importance of subsurface storage

The rivers and streams are monsoon fed with monsoon rainfall contributing more than 75% of the total rainfall and 80 - 90% runoff is generated during this period. Annually, the rainy days vary from 12 to 100 and the natural recharge is restricted to this period only. In arid areas, rainfall varies between 150 and 600 mm per year, with even less than 10 rainy days. Most rainfall occurs in 3 to 5 major storms lasting only a few hours. The annual rate of potential evapotranspiration is exceptionally high, ranging from 300 to 1,300 mm. The climatic features in arid areas are not favourable for creating surface storage and thus, artificial recharge becomes the only option.

Surface storage (large dams) contributing only 174 bcm of surface water has already given rise to many political conflicts and other problems such as water logging and increase in inland salinity, etc. The construction of envisaged additional surface storage of 75 bcm till 2025 is not possible within stipulated

time period because of many environmental, social and political issues at stake. It is anticipated that the political/personal conflicts over sharing of surface water between riparian states will increase with increasing demand for water for irrigation, industry and drinking. In the existing scenario, the Indian government does not control groundwater development or the cultivation of water intensive crops in arid areas with low-permeable hard-rock aquifers. Because of the environmental and socio-economic issues, the various kinds of subsurface storage structures provide a solution without political conflicts, disagreement on sharing or using water.
It is estimated that out of the total availability of 4,000 bcm of rainwater, the surplus monsoon runoff is 1,240 bcm. At present, the surface water storage comprises only 174 bcm and it is expected that the storage will increase to 371 bcm by 2050. The projected demand of 784 bcm by 2025 is possible only if non-committed monsoon water is utilized for creating subsurface storage of 214 bcm (Central Groundwater Board, 1996).

4 An overview of artificial recharge projects in India

The history of water conservation and recharge dates back to more than 3000 BC. Since then percolation tanks, check dams and water storage ponds have been constructed in arid and semi-arid areas of rural India to store water, which also indirectly recharges the groundwater. However, scientific experiments with artificial recharge using different techniques started between 1976 and 1980. Feasibility studies were carried out on some of the projects using techniques such as, induced recharge combined with injection wells, check dams, subsurface dykes and surface spreading. The real break through of artificial recharge was between 1995 and 2002, when with central financial assistance of US$ 6 million, a number of artificial recharge projects were taken up in rural areas, using a wide spectrum of techniques. The systems vary from place to place depending upon the hydrogeology, source of water available in a particular area. A broad categorization of recharge techniques is given in Figure 1.

The execution of projects was supported with mass awareness programmes, with seminars/workshops organised all over the country and with publications (Central Groundwater Board, 2000). Encouraged by successful demonstration projects, a master plan was prepared to implement enough artificial recharge structures such as percolation tanks, check dams, cement plugs, gabbions etc, to utilize the non-committed monsoon surplus runoff for subsurface storage of 36 bcm of water (Central Groundwater Board, 2002).

The master plan envisages a total area of about 450,000 km^2 for artificial recharge to store 36.155 bcm of water. This will be achieved with among others 3.7 million roof top structures in urban areas and 0.225 million roof top structures in rural areas, 37,000 percolation tanks (each of 0.2 mcm), 110,000; check dams/Nala bundhs (each of 0.03 mcm), 48,000 recharge shafts/dug well recharge (each of 0.03 mcm), 26,000 gully plug/gabbion structures (each of 0.005 mcm,) and further the development of 2,700 springs in hilly areas.

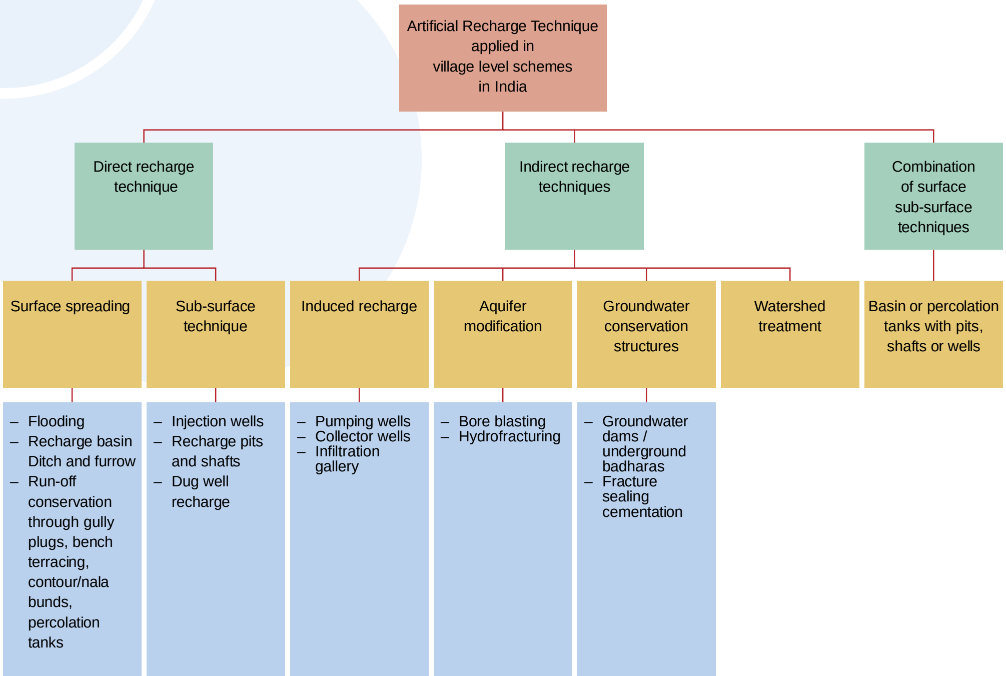


Figure 1. **Artificial recharge techniques applied in village level schemes in India.**

This way it is possible to create 36.155 bcm subsurface storage capacity in critical areas, meeting the increasing demand of agriculture and drinking water without any conflict issue.

5 Case study

The present case study pertains to an intensively irrigated area where the groundwater development amounts to twice the natural recharge, resulting in a watertable declined of 10.53 m since 1972. In order to stop this declining trend and to increase the discharge of the tubewells, the project was conceived to use the monsoon runoff, which is available in the drain by constructing lateral shafts, vertical shafts and injection wells as recharge structures (Figure 2). The exploration for the aquifer system indicates the presence of a granular zone between 4 and 26 m depth, therefore, the depth of the vertical shaft was kept about 6 m.

In this scheme, the recharge studies have been carried out in the Dhuri Drain between the stretch of RD 47.56 and 16.77 km i.e. in the 30.79 km length of Dhuri Drain. At RD 32.1 Km and RD 32 km the drain is crossed by two distributories; Sheron and Sangrur Distributories. The distributories are unlined and breach occasionally, therefore, 295 m long of distributories were converted in to inverted filter, with gravel & sand up to 3 m depth for augmenting the groundwater recharge (Figure 3 a).

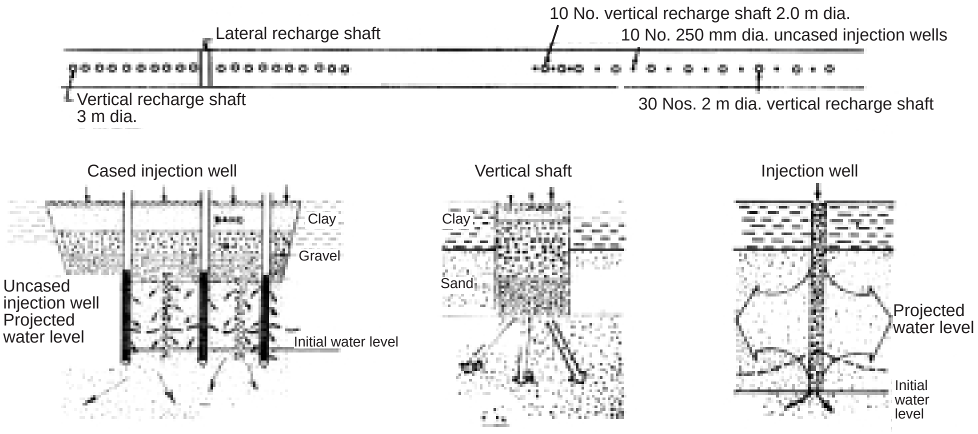
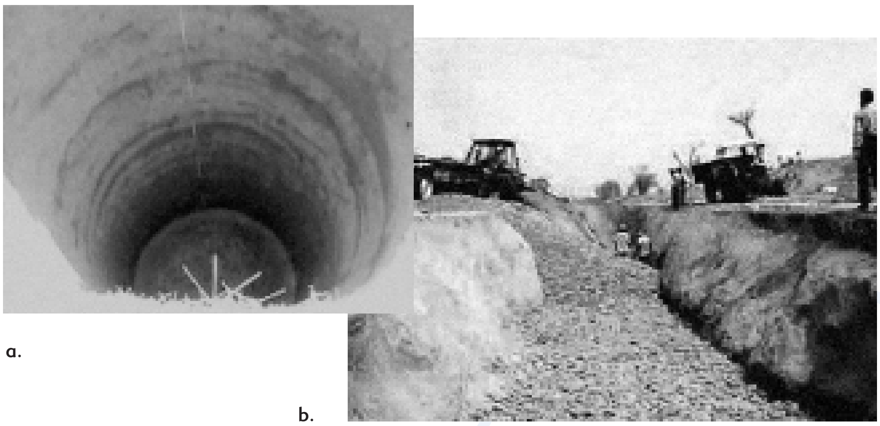


Figure 2. Artificial recharge, Dhuri drain in Sangrur District, Punjab.

All along the 30.79 km of the drain, 30 vertical shafts 2 to 3 m in diameter up to 6 m depth depending upon the subsurface strata were constructed. These shafts were filled up with sand and gravel pack to act as inverted filters so as to provide silt free water for recharge (Figure 3 b). In between the shafts, 30 injection wells were constructed. The recharge through inverted filter and vertical shafts made it possible to have an effective recharge of 4.79 mcm of silt free water (Figure 4).



a.

b.

Figure 3. Construction of shaft (a) and filling drain with inverted filter (b).

Figure 4. Injection wells being recharged from the trench.

6 Impact assessment

The direct impact of this project was a rise of the water table of 0.25 m over an area of 30 km^2 and an increase of the yield from 150 tubewells, benefiting 200 families in the area. The supplement recharge per year amounts to 39 million m^3, which can support 130 additional shallow tubewells. It also helps to save pumping energy due to rise in water level (26 Mw per year).

References

– ***Central Groundwater Board*** (1996) National prospective plan for recharge to groundwater by utilising surplus monsoon runoff. 1 - 24.
– ***Central Groundwater Board*** (2000) Guide on artificial recharge to groundwater. 1 - 93.
– ***Central Groundwater Board*** (2002) Master plan for artificial recharge to groundwater in India. 1 - 116.

4 The significance of subsurface water storage in Kenya

Author Sammy Mutiso

1 Background

Over 80% of Kenya consist of arid and semi-arid lands (ASAL)(Thomas, et al, 1997:105; Republic of Kenya, 2002). Arid areas receive less than 400 mm of rainfall annually and the semi-arid areas get between 400 and 1000 mm annually. Low rainfall, strong variations in rainfall in space and time; high temperature and high evapotranspiration rates characterize these areas.

ASALs are gently sloping, with usually less than 5o gradients. Soils are usually sandy, fragile and highly erodable. ASALs are below 2000 m elevation and usually have many sandy seasonal streams. Water points in these areas are few and far apart; in some places people and animals have to walk 30 km to reach the nearest water point during the dry season.

Furthermore, the time distribution of the rains is very skewed: short to very short 1 - 2 months wet periods twice a year followed by long dry hot periods. The wet periods are also erratic: one in three rainy seasons is below normal. Often rains occur in storms with high intensities which cause high runoffs carrying lots of the easily erodable soil and little recharge.

The low rainfall combined with high evapotranspiration coupled with runoff losses from the catchment where the precipitation occurs, greatly reduces the areas inherent potential. It is in these regions that water harvesting is of paramount importance: it holds the key to improved water supply.

Bulk and production water

People in the ASALs need two categories of water: firstly, bulk water for domestic use and watering their animals and, secondly, water for producing foods and grow pasture for the animals. Indeed, these areas are favourite for beef cattle rearing. These areas produce about 64 - 80% of the national beef cattle. Even though the ASALs in Kenya are harsh, they provide the bulk of the country's meat. Figures for crops are not available, but ASAL dwellers produce most of their own food and have a balance to sell to the towns (GoK, 1990). Provision of water in the ASALs will increase their production potential, improving the livelihoods of its people. Since there are no external sources of water, the solution lies in the maximum use of the precipitation within the catchment.

Rivers have no water of their own

In most ASALs, the quest for water is not depending on the absolute amounts of precipitation, but on the fraction retained. If a substantial portion of the received precipitation was retained in catchments, the situation would be greatly improved. It is usual to see rivers in full spate flows after a rainstorm, but rivers have no water of their own, all this water is run-off from the surrounding lands. It is on record that about 70 - 90% of the precipitation received in the ASALs is lost through run-off into the drainage channels (Thomas, 1997). Only about 20% of the precipitation percolates into the soil and can be used.

Unless water-harvesting techniques are employed, the already bad situation can get worse. Water harvesting by use of conservation measures in the catchments would hold water long enough on the land to allow percolation into the subsurface. Water would be released slowly from these storage into the river channels and storm flows would not occur. This would increase the length of time the soil remains moist and suitable for food production without water logging and damaging of the plants.

Optimization of land use

Because lack of water limits production in the ASALs, development will not proceed without stable water supplies in these areas. Water availability is a central precursor to investment in the land for production. Not absolute lack of precipitation, but mainly lack of retention limits the water availability; 70% of the precipitation is lost to surface runoff. (Rowland, 1993).

A further significant amount is lost through evaporation because of inadequate ground cover and open storage such as surface dams. To increase land potential in ASALs, the water holding capacity of the soils must be improved: surface run-off must be checked, water retention structures constructed and maintained and inherent vegetation enhanced to provide ground cover and improve water circulation through evapotranspiration. All these factors will ultimately influence local precipitation, its frequency and its distribution.

The role of evapotranspiration in a localized precipitation scheme is largely ignored. This phenomenon works through the build up of humidity above localized vegetation, which, combined with the moisture from the reservoirs of the hydrological cycle such as lakes, seas and other open water bodies, leads to the formation of clouds and precipitation. It is deemed that the major part (5%) of the rainfall in the forest arises in this manner (Dupriez and Leener, 1998).

Since the frequency and severity of droughts has increased in the recent past, surface water storage will continue to suffer severe evapotranspiration losses. Subsurface water storage will, therefore, become much more important in the ASAL areas of Kenya.

Looking into the future

I envisage a situation where several different methods are employed to capturing and store water from precipitation. The synergetic effects created will greatly outweigh the intensification of any single method.

Conservation and management of water on the land by using terraces and contour bunds slows down runoff from agricultural lands and making more water available for crop and pasture production. Sand dams in river channels will store bulk water for domestic use and livestock. Further, the bulk water behind the dams can be used to grow tree seedlings for re-vegetation. When the trees grow, they play their part in the control of runoff and increase percolation, thereby increasing productivity of the land. The trees and other plants in the area add to the stored energy due to evapotranspiration thereby facilitating trapping and storing energy from the sun.

Such a situation will also save the total energy in the system. This energy can be utilized for further development of the system. For example the human energy and time saving on water chores which is highly significant if average distance to water sources for households is reduced from 10 to 2 km could be invested in improving production of the land by instituting more water conservation measure.

In my view, the catchment approach is best to achieve these aims. For the purposes of water harvesting and recharge, a catchment is defined as an area bounded by watersheds draining into an outlet. For effective management, large catchments should be divided into smaller units. The main objective in the catchment should be to retain and percolate as much water as possible in the catchment, thus reducing both runoff and erosion; whilst allowing excess water to drain off with minimum damage.

All the land belongs to a community. In most rural areas it is their most important resource. Thus, improvement and optimal use of this land is the basis for development. For the recharge systems to be effectively utilized, the community should be the starting point and be fully involved.

2 Recharge techniques used in Kenya

The population increase has necessitated the capture and storage of water in the ASALs by the new settlers. Their life is tied to water as it is to air and food. Since plant growth depends on water flow from roots to leaves, food production is reliant on groundwater. Meaningful development is therefore, depended on the ability to capture, store and use water efficiently.

With the increasing pressure on land in Kenya, ASALs where rainfall is erratic and water loss due to runoff high, are more and more being used for agriculture. Surface run-off harvested in these areas is used for crops and livestock. With the increased drought frequency and severity of droughts in the 1970s and 1980s there has been an increased awareness of water harvesting in Kenya (Thomas, 1997).

There are several techniques used for water harvesting for recharge in Kenya. These include:

– Trash lines: these are made of crop residues, are simple and easy. They are effective on low gradients. Grass and weed develops along the trash lines and stabilizes them in about 2 years. The soil trapped then reinforces these lines;

- Grass strips: these are developed by leaving strips of unploughed land with or without seeding with grass. As in the case of trash lines above, water and soil is retained here;
- Micro catchments: these are several types of different types of collecting pits, which are used for the establishment of trees and growing of value crops such as bananas and fruit trees;
- Contour ridges and bunds: these are furrows constructed on the contour by throwing the soil downwards. They can be made of earth or stone. They store water in an excavated area. Crops in this system have greater yields and especially in seasons of lower than normal rainfall;
- Retention ridges: these are large ditches that are designed to catch and retain all incoming runoff and hold it until it infiltration to the ground (Thomas, 1997:98). They are used where runoff from the road is diverted onto cultivated lands;
- Terraces (Fanya Juu): the Fanya juu terrace is made by digging a ditch and throwing the soil uphill to form a barrier ridge. The barrier ridge retains water and soil. They are used to improve retention and control erosion on cultivated lands improving crop production;
- Earth dams and pans: these are raised banks of compacted earth, built at the downstream end of a hollow. They are liable to rapid silt up if the catchment is not conserved or denuded by animals. Many examples exist where the structures are completely dysfunctional in 10 years. Also, due to high evaporation, a lot of water is lost;
- Sand dams: these are made by building a wall across a riverbed, which traps water. They have minimal losses of water due to low evaporation and have a long life. They have high lateral and vertical recharges and have a great potential of creating shallow artificial aquifers.

3 A low level technology application for subsurface recharge in the asal's of Kenya: a case study of sand dams of Kitui

Definition

A sand dam is an impervious barrier across an ephemeral river, which holds water and sand on the upstream side.

Significance of sand dams

Although the sand dam technology has been known for 3000 years since the time of the Babylonian Kingdom, it has not been applied at a large scale. This might be because it is a low-key technology and there is no grandeur to it. As a result its full capacity has not been realized and developed, even though it is one of the major systems to aid communities living in arid and semi arid lands with ideal condition for its application.

Seasonal streams abound in the arid lands in large areas of Kenya, after the runoff has disappeared the riverbed is full with sediments. It is in these streams that sand dams are being constructed. When many of them are made along the stream, the ecological pressure is spread along the river. Which would not have been the case if only one water point was made available. People and animals have their water nearer to homesteads and a wider area is influenced by the local retention of water. This then is the significance of this simple technology.

Sand dams have mainly been constructed in Eastern Kenya. Fewer numbers of dams are found in Western and Northern Kenya.

Sand dams and people

The dams in the Kitui sand-dams programme are developed in co-operation between the community and the non governmental SASOL (Sahelian Solution Foundation). The community's desire to develop their water resources for their needs, drives the programme.

Location, design and construction

The location of a sand dam should be chosen such that: it is feasible on technical grounds, it has high storage capacity, it has minimum cost and it is convenient to the community using it.

The selected location is excavated to reach a firm impermeable layer as founding layer for the dam. This layer may be base rock, clay or murram and is usually uneven. Only after excavation, can the base of the dam be mapped out, a profile and other dimensions chosen (length, crest, height). The dam design then also takes into account allowance of Peak River flows without impediment. A bill of quantities is made on this basis of the design.

In Kitui, Kenya, dams are made of masonry, because this is relatively cheap and masonry has a long lifetime with low maintenance: some sand dams made fifty years ago of rubble stone, are still functioning without any repairs. There are two options of construction. The first option is to build a wall-facing, which is filled with stone and mortar. The second option is to construct a timber formwork, which is filled with stone and mortar.

Other materials for dam construction include plastic foil, galvanized iron sheets and clay lugs. However these are used where stone is not readily available.

Hydrology of sand dams

In general he water yield from a sand dam is considered a function of the volume of the sand in the reservoir and the extractability of water from the sand. The basic assumption is that the sand dam only holds water in the sand. SASOL, however, has always argued that there is much more water held in the dams than that in the sand behind the dam. In a recent study (Gathuru, 1990; Frima, et al, 2002) it was found that the water table behind the dam extended almost horizontally into the banks for distances up to 200m on either side of the dam and 500m upstream. Downstream the water table is lower but equally extensive. Thus the dams hold more water than previously reported in the literature.

Synergies created by sequential dams

A series of sand dams in the same channel have a greater effect on the channel per area than single dams. As seen earlier, the ecological damage on a single point water source is avoided and is likely to get a higher rise in water table than in individual units. The rise of the water table is continuous along the channel and recharge into soil storage spaces is hence much more effective.

Cost of sand dams

The cost of a 60 m^3 sand dam in Kitui with a minimum design lifetime of 50 years and a yield of minimum 2,000 m^3 is 6,000 Euros. This is equivalent to 6 tanks of 46 m^3 at 1,000 Euros each.
Evidently it is cheaper to build one sand dam which will serve 50 households at the cost of 6 tanks which would serve only 6 households.

Advantages and limitations of sand dams

Storage of water in sand bodies has many advantages. Firstly, evaporation is limited. Secondly, they occupy low value land. Thirdly, recharge is automatic and immediate after a storm. Lastly, the structures are low maintenance.

The main limitation is that the yield is determined by the quality of sand and the surrounding soil properties.

The effects of sand dams

Sand dams retain water thereby facilitating infiltration into the ground and sideways into the banks of the channel. Since infiltration depends on both time and the nature of the soil, subsurface storage of water is extremely important especially in the ASALs where the rain season is relatively short and the rain falls in storms.

As the water table rises in the drainage channel the subterranean flow from the surrounding area into the channel is slowed down, as a result of changes in the hydrostatic head.

The readily available water in the sand dam firstly increases the amount of water for domestic purposes, and reduces the amount of time spent on water chores. It facilitates the installation of improved extraction methods such as improved extraction wells, which leads to water of a better quality.

Subsequently, people start using the water in the dams for small-scale bucket irrigation. In some cases larger-scale irrigation systems have been developed with pumps and storage tanks. The vegetables grown increase land values and prompt the community to further improve their land through water conservation, which increases the yield of the sand dam.

Lastly, during the second and third year of a new dam, the community is sure the water in the dam will last all year round. Tree-seedling raising starts leading to replanting and introduction of tree products as economic goods.

Conclusion

Sand dams are a low-level technology, cheap enough to be made by the local community with the available resources. Sand dams thus enable this community to solve its water problems and improve the livelihood of its people. It is recommended that the catchment approach be implemented systematically and in a sustainable manner.

References

- ***Dupriez, H and De Leener, P.*** (1998) Trees and Multi-storey Agriculture in Africa. CTA publication, Wageningen, the Netherlands.
- ***Engelman, R and LeRoy, P.*** (1993) Sustaining Water: Population and the Future of Renewable Water Supplies. Population Action International, Washington DC.
- ***Frima G.A.J. et al*** (2002) 'Sand Storage Dams: Kitui District. A manual on Monitoring the Groundwater Levels Around a Sand Storage Dam' (unpublished manuscript)
- ***Gathuru, N.*** 'Estimation of Recharge from the exponential Decline of Base flow in the upper East catchment of River Ewaso Ngiro' in 'Nairobi University Geological Magazine 1990'.
- ***Gould, J. and Nissen-Petersen, E.*** (1999). Rain Water Catchment Systems for domestic supply: Design, Construction and Implementation. Intermediate Technology publications, London.
- ***Kenya, Republic of*** (2002) 'Country Strategy on the Integrated Water resources management' Ministry of Environment and Natural resources (unpublished manuscript).
- ***Lee, M.D. and Visscher, J.T.*** (1992) Water Harvesting: A guide to planners and Project managers. Technical paper series No 30, IRC International Water and Sanitation Centre, The Hague, the Netherlands.
- ***Rowland, J.R.J (ed)*** 1993). Dry Land Farming in Africa. Macmillan education limited, London and Basing Stoke.
- ***Thomas D.B. et al*** (1997). Soil and Water Conservation Manual for Kenya. Ministry of Agriculture, Livestock Development and Marketing, Nairobi, Kenya.
- ***Tiffen, Metal*** (1994) More People less Erosion: Environmental Recovery in Kenya. Acts press, Nairobi, Kenya.
- ***Young A.*** (1989) Agro forestry for Soil Conservation. C.A.B International, Willingford, UK.

5 Enhancement of groundwater recharge in Hungary, in particular bank filtration for drinking water supply

Author Zoltán Simonffy

1 Introduction

The new EU Water Framework Directive emphases – among others – the provision of sufficient supply of water for sustainable and equitable water use and promotes mitigation of the effects of droughts. To satisfy these requirements efforts are needed towards a new, more efficient groundwater resources management, including the consideration of environmental and economic aspects as well.

The present paper outlines major features of water management in Hungary in respect to the importance and sensitivity of the groundwater resources of the country and summarises different application of enhancement of groundwater recharge, in particular the use of bank filtered water for the supply of drinking water.

2 General features of the Hungarian water resources management

Hungary is located in the deepest part of one of the closest basins of Europe, the Carpathian basin (Figure 1). The majority of surface water arrives from the surrounding countries. In total 24 rivers bring water into the country (110 km^3/year in average). Three large rivers (the Danube, the Drava and the Tisza) leave the country after collecting the Hungarian runoff (6 km^3/year), which is by the way the smallest in Europe: only 5 % of the total outflow. The characteristic specific values of the renewable surface water resources are 64 mm/year, 2 l/s/km^2 or 600 m^3/cap/year. Areas far from the large rivers suffer from shortage in water. The reason for this can be derived from the relief (two third of the country is under the altitude of 200 m) and the special climatic conditions. The potential evapotranspiration exceeds the precipitation from April to October, and consequently the runoff in summertime, when the peak of water demand occurs, is very low. The relief of the country is also not favourable for reservoirs: the actual total storage capacity amounts 500 million m^3, which is only 8% of the total annual surface water flow and hardly extendable. Furthermore, the spatial distribution of the home runoff is uneven: in the right side catchment of the Danube (Transdanubia) the runoff conditions are more favourable, while in the plain, especially in the eastern part of the country, large areas have no natural runoff.

The large rivers have transported a huge amount of sediment during the Pliocene and Pleistocene Ages, forming a thick alluvial deposit (Figure 2). Except fissured rocks, groundwater is available throughout the country in sufficient quantity.

The limited surface water resources along the small and medium water courses at one hand, and the aquifers with good permeability providing almost everywhere

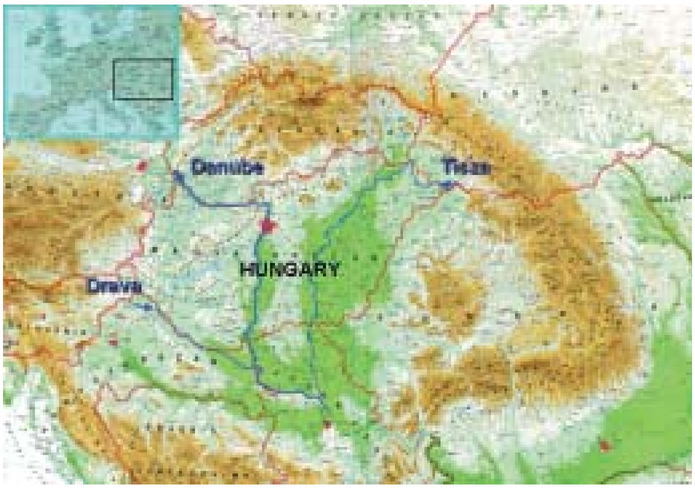


Figure 1. The Carpathian basin.

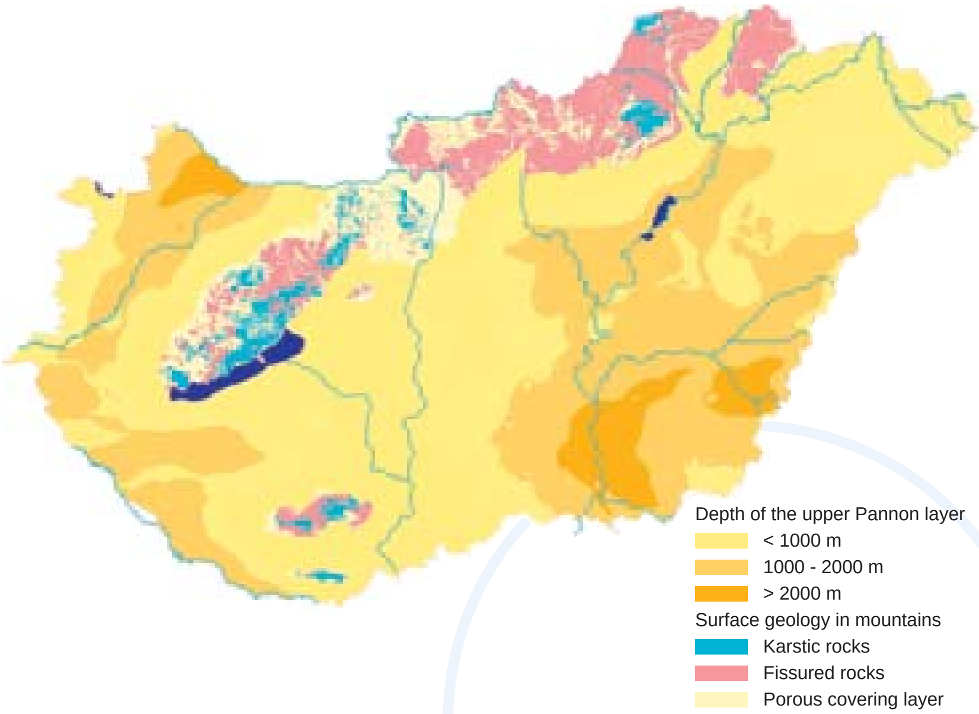


Figure 2. Geological map of Hungary with the depth of the Pannon (Pliocene) formation.

cheap local supplies for the water demand. This has resulted in the present situation, where 70% of the total abstraction (except cooling water) is from groundwater. Beside the traditional dominance of groundwater in the drinking water supply (94%), abstraction of groundwater for industry and for irrigation has gradually increased and nowadays it exceeds the amount used from surface water (Figure 3). Economic changes in the years of 90s (recession in industry and agriculture and increasing price of the water) resulted in considerable decline of water use, especially in the case of surface water abstractions.

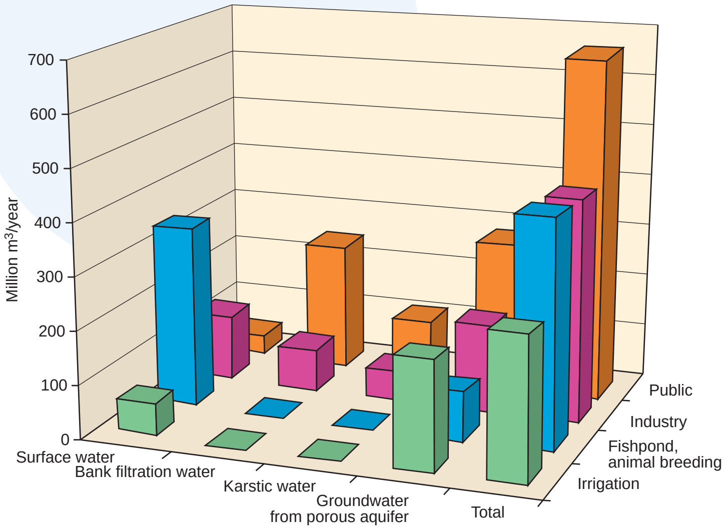


Figure 3. Distribution of water use in Hungary.

The public uses 660 million m^3 water yearly, 94% of that is abstracted from groundwater; 105 million m^3 from karstic resources; 275 million m^3 from porous aquifers and springs of fissured rocks and 240 million m^3 is bank filtered water. It should be noted that the drinking water supply of Budapest completely relies on this type of resource. The industrial water use (except energy sector) is 425 million m^3/year; here the contribution of the groundwater is 70%. Fishponds use entirely surface water, while animal watering is supplied from groundwater. Irrigation actually needs 275 million m^3. The distribution between surface water and groundwater is 1:3. Summarized, out of the total water abstraction of 1.8 million m^3, 1.2 million m^3 originated from groundwater. Although the abstraction of 320 million m3 is considered a groundwater resource, bank filtered water as a matter of fact is the result of direct enhancement of the infiltration from surface water by wells drilled in the vicinity of riverbanks.

Considering the above-described high pressure on the groundwater resources, it is important to access the available resources. In karstic and porous aquifers it has been determined based on the prescription of the EU Water Framework Directive, i.e. the long-term average recharge is decreased with the environmental demand of the groundwater dependent water courses (base flow in low flow period[1]) and terrestrial ecosystems (transpiration from groundwater[2]). This is 250 and 1450 million m^3/year respectively. In the case of bank filtered water resources the length of the convenient river sections and the filtration capacity is the dominant factor, resulting in a capacity of 1800 million m^3/year. Comparing this amount with the abstracted amount, the ratio of exploitation at country level is 62% for karstic water, 53% for porous aquifers and 18% for bank filtered water.

1 In summers, during long periods without surface runoff, ecosystems of small water courses are generally dependent from the amount of infiltrated groundwater, since it provides the majority of the flow in the riverbed.

2 If the growth of the vegetation needs more than the summer rainfall or respectively the periods without precipitation are too long, surplus water is only available to plants where the root zone receives supply from the groundwater by capillary rise. In discharge areas the vegetation is adapted to the available surplus transpiration from groundwater, thus the impact of the groundwater abstraction should be limited.

But behind this favourable global values, regions in critical conditions can also be found (Figure 4) where some karstic aquifers are overexploited. In the Transdanubian region mining activity still continue (formerly it was much more extended) and in the northern part the drinking water supply of the city of Miskolc is also still dependent form groundwater. The porous aquifers are seriously overexploited in the eastern part of the country due to the too high industrial and agricultural use. Alternative resources are surface water for irrigation and where possible bank filtered water for watering and industry. Also new solutions of recharge enhancement should be considered in the process of the preparation of river basin management plan.

In respect to future water requirements, agricultural demand forms the most important element of the assessment. However there are still many uncertainties with respect to structural changes in relation to EU-accession, also the real demand for irrigation is not well known. Public demands are expected to decrease slightly, while the industrial demands after a slight redistribution in space will remain approximately the same.

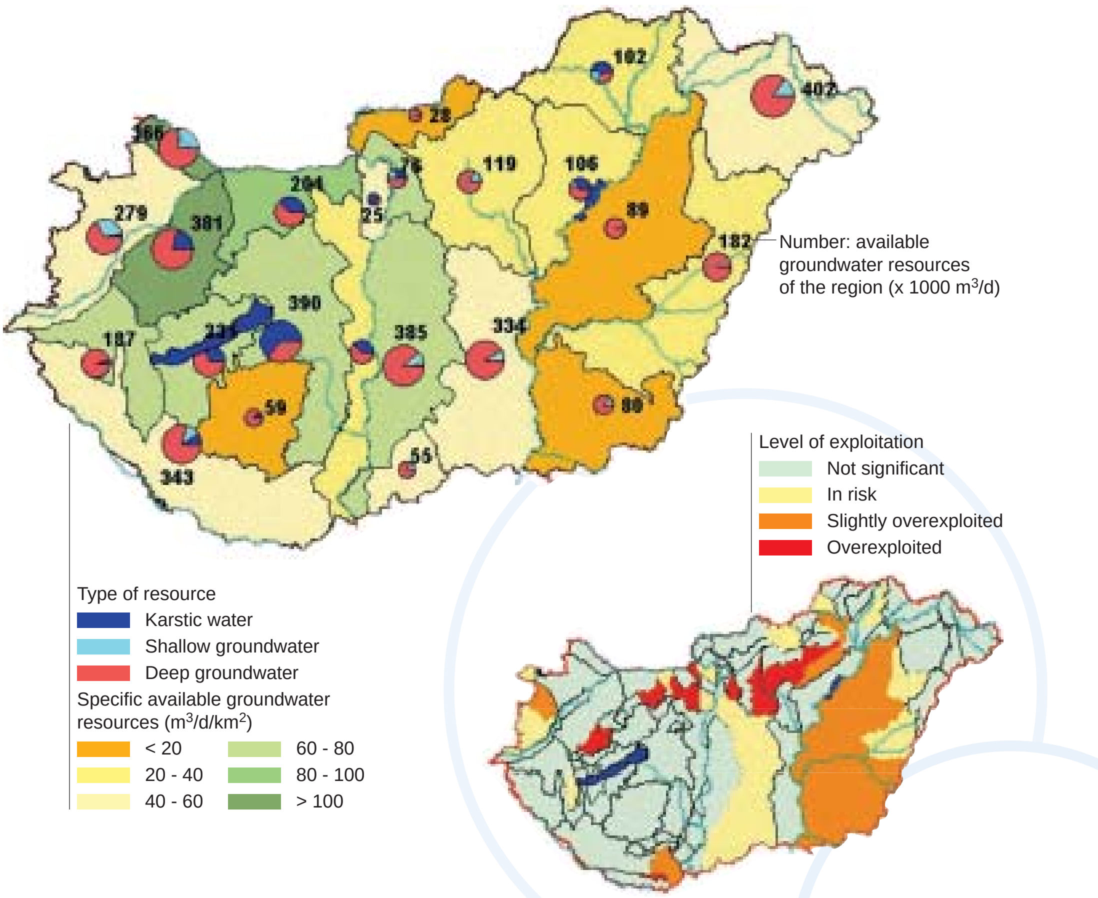


Figure 4. Available groundwater resources in Hungary and their ratio of exploitation.

Hydrological conditions are presumably reacting sensitively to potential climatic changes. Depending on the scenarios of the global changes, summer temperature can increase by 0.2 - 0.4 °C/decade, while winter temperature can increase by 0.2 - 0.8 °C/decade. Evaporation will also increase, while precipitation will decrease in the south-eastern part, which is already in critical situation. A recent assessment showed, that the specific water demand for irrigation can increase by 20 - 50% due to the impact of the climate change: (i) decreasing precipitation in the growing season and (ii) increasing water demand of the vegetation because of the higher potential evapotranspiration. On the other side, the additive impact of the changing potential evapotranspiration and precipitation will result in considerable reduction of surface water runoff (30 - 60%) and recharge of groundwater in the south-eastern part of the country (25 - 80%). It is likely that the public and industrial water demand can be met, the bottleneck is to meet the irrigation requirements, whose social priority and economic weight is lower. A sustainable solution is to adapt the need for irrigation gradually to the available water resources. However changing resources management should also be envisaged. The critical situation could be mitigated by applying more economical and efficient irrigation technology and by considering the free resources (bank filtered water) for public and industry. This way increasing free resources for irrigation could be increased, by retaining and infiltrating excess water. It is to be noted that there are hardly any possibilities for additional surface reservoir capacities.

3 Recharge enhancement in Hungary

In this chapter selected cases will be presented where the method of enhanced recharge is applied with different aims and at different scales.

Artificial recharge of groundwater along the old riverbed of a diverted river (Danube)

In 1992 the Danube was diverted to the side canal of a hydropower plant at the Slovakian border. Only an ecological minimum discharge remained in the old riverbed. The consequences for groundwater was a considerable drop in water level, endangering the sensitive ecosystem of the side branches of the Danube and the larger vicinity, where previously the Danube has played the dominant role in influencing groundwater level fluctuation (Figure 5). Restoration of the previous groundwater conditions is solved with an extended artificial recharge system using the branches of the original side arm system in the flood plain and former irrigation canals in the protected side. In this case the aim of the artificial recharge is to mitigate the harmful impact of another human impact. This solution needs a lot of water (20 - 40 m^3/s depending on the season). As the Danube can provide the necessary discharge to maintain the groundwater at optimal level in the majority of the area this is a feasible solution. Except for a approximately 200 m wide strip between the old riverbed and the closest branch, where the actual low Danube level is still the dominant boundary condition.

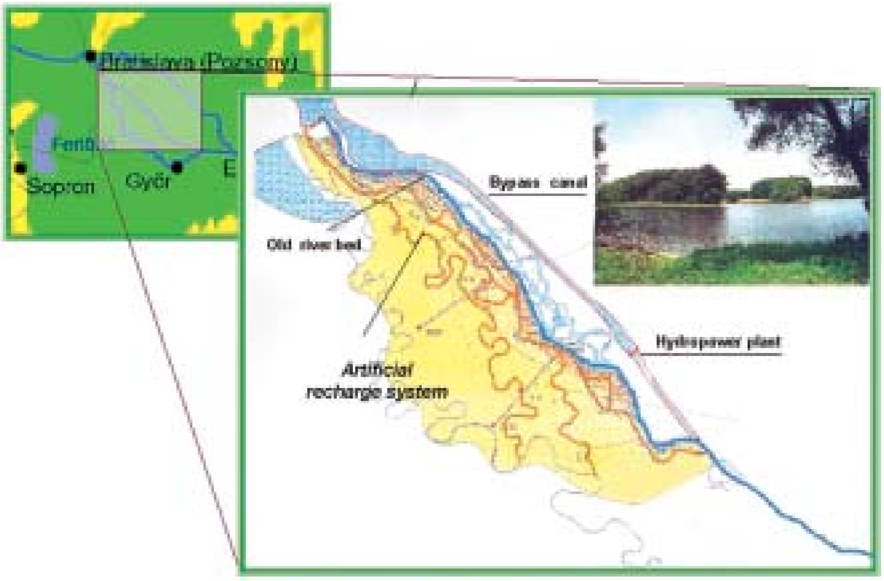


Figure 5. Artificial recharge system in the Szigetköz region.

Scattered recharge: sewage water infiltration in settlements

While evaluating the special characteristics of the Hungarian water resources management, the deposition of sewage water should also be mentioned. The abstracted groundwater, after it has been used, is collected and discharged to surface water where sewerage is available. On the other hand, Hungary is characterised by a high gap in water infrastructure: the drinking water supply is almost total (98 %), but only around 50% of the population is served by sewerage. In the non-sewered small and middle size settlements the majority of the sewage water infiltrates into the soil via inappropriate septic pools. The treated and transported sewage water is estimated at 340 million m^3, while the infiltrated sewage water is estimated at 280 million m^3/day, approximately 90 million m3/year can be considered as surplus recharge. As a result of the ongoing sewage water collection and treatment programme aiming at satisfying the EU-requirements, the infiltrated amount will considerably decrease. This approach has to be revised in areas with critical ratio of exploitation, namely in the eastern part of the country. Beside the advantage in enhancement of the local recharge conditions, maintenance of sewage water infiltration with environmental friendly technology can decrease the pressure on the surface water quality. The infiltrated amount can be considered as resource for irrigation in the settlements and in their surroundings.

Excess water used for mitigating the harmful impact of droughts

Hungary had already some bad experiences from the changes in the meteorological conditions. In the middle of Hungary in a large recharge area of about 6000 km^2 between the Danube and the Tisza rivers (see Figure 1) the decline of groundwater levels over a dry period of 12 years exceeded 4 m, due to the deficit in precipitation (recharge) and the increasing groundwater abstraction for covering the higher water demand of irrigation. However, during the last 7 years with approximately average meteorological conditions the decline was stopped, and an upward trend has been observing. This case has drawn the attention to the sensitivity of the region for climatic changes. The root of the problem, i.e. the inappropriate land use is still maintained, thus the problem can arise again in the case of returning dry period or considerable change of climate. The problem is regional. Field experiences have showed that at that scale, artificial recharge from canals cannot be efficient, as their impact is only local. The canal system should be so dense that it makes the solution extremely expensive. The right solution is the adaptation of the land use to the fact that the region is sensitive to changes in meteorological conditions. The problem and the possible solution are valid for other regions as well.

The seasonal alteration of the precipitation is large: winter and spring often bring too much precipitation, which causes seasonal inundation in flatlands covered by less permeable or frozen soil. The lowlands of the country are threatened by the occurrence of excess water (Figure 6a). In agricultural area the excess water can damage plant cultivation, so an extended canal system (appr. 40 000 km long) has been constructed for drainage. In contrast, the eastern part of the country is endangered by drought (Figure 6b). The index over 7 refers to serious damages for the vegetation, here irrigation is necessary for preventing serious drought damage. Figure 6 clearly demonstrates the overlap of the areas endangered by excess water and droughts. Even more, due to extreme meteorological and hydrologic conditions excess water and drought can appear in the same place

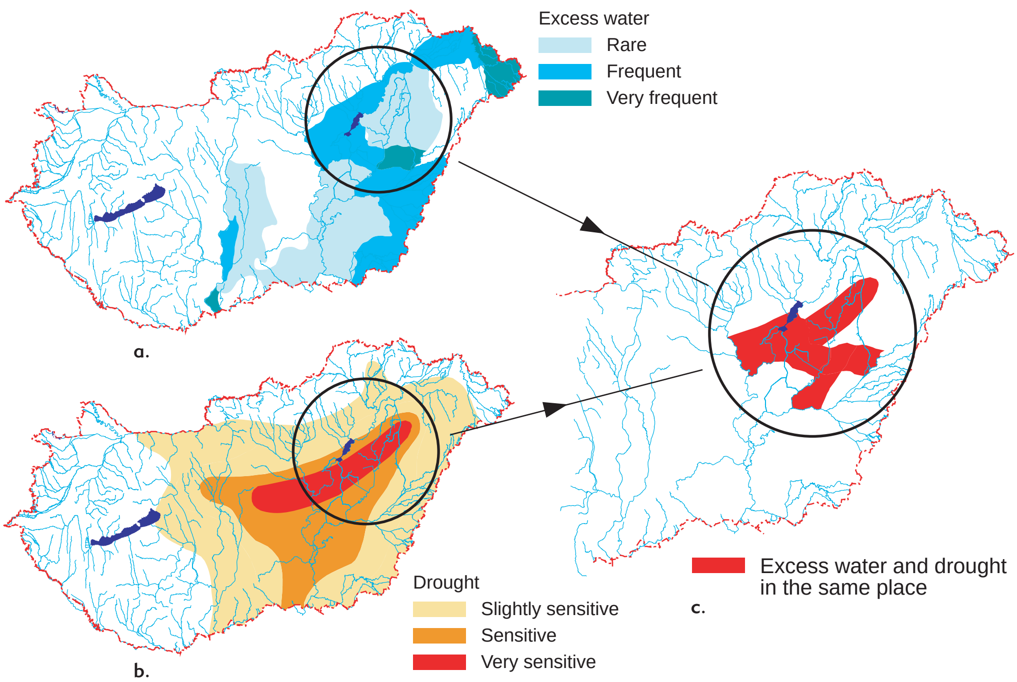


Figure 6. Area under pressures of excess water and droughts, regions for possible enhancement of recharge.

and in the same year. Only a few canals are used with double functions. Here a new strategy is needed: instead of draining excess water out of the catchment it can be collected in areas with permeable covering layers, where it will infiltrate to the groundwater. In summer the stored water can be abstracted for irrigation purpose. The system is mosaic-like, the application needs appropriate adaptation of the land use, which is facilitated by the actual situation of decreased agricultural production and being imminent of the structural changes of the agriculture because of the procedure of joining the EU.

Bank filtered water abstraction

Bank filtered water[3] covering one third of the public water demand, is of crucial importance for the drinking water supply in Hungary. The drinking water supply of Budapest is entirely relies on the bank filtered water of the Danube. Why is it advantageous? The abstracted amount is limited by the filtration capacity of the bank only, the discharge of the river is an order of magnitude greater with than the abstracted amount. Practically there will be no limitation from the resources side, which gives this resource a high security, especially if the sensitivity to climate change of other groundwater resources is considered. The advantage compared to the direct abstraction of surface water is the reduced treatment requirements

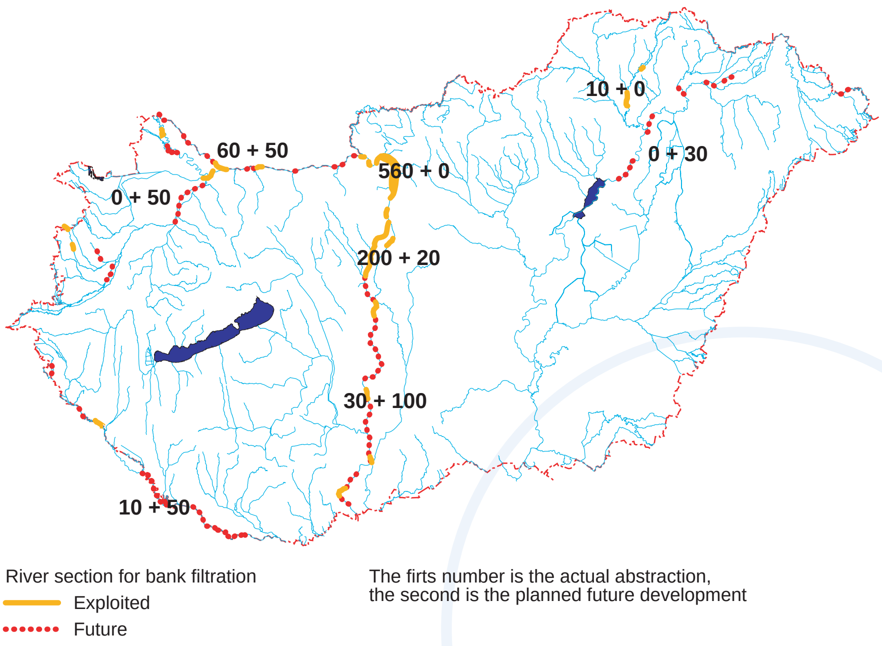


Figure 7. Existing and future bank filtered river sections in Hungary.

3 Bank filtered water theoretically means all water infiltrating from surface waters to the groundwater. The amount can be largely increased by pumping wells drilled close to the riverbed, even in the case where originally the surface water was draining the groundwater. In the abstracted water three types of water is mixed: (i) surface water originated infiltration with relatively short travel time from the bank section in front of the wells, (ii) the same origin, but from the bank section at the two edges of the well field with medium travel time, (iii) precipitation originated recharge from the so called background area with travel time up to hundreds of years. By definition in Hungary, the well field is considered as bank filtered type, if the abstracted amount contains more than 50% from the (i) type of water.

of the water. The natural filtration capacity of the exploited river sections are very efficient, no micro-pollutants have been found in the abstracted water. This advantage is valuable for users requesting drinking water quality, so for public, watering and some industrial use, but not for irrigation.

Well fields (Figure 7) exploiting bank filtered water are mostly along the Danube, only two can be found at other rivers (one in the south-western part of the country, and one in the northern part). The estimated ratio of the surface water is 80% in average. The actual use is 0.9 million m^3/day (75% for public purposes), the further potential capacity is approximately 4 million m^3/d, out of that 300 000 m^3/d capacity is protected as designated future water resources.

4 Cases of bank filtered abstraction in Hungary

Szentendre island, shaft wells with horizontal screens

Upstream Budapest the Szentendre island (Figure 8) consists of a sandy-gravely deposit of the Danube (after the Visegrád pass the river has formed several islands), which is perfect for bank filtration. The coarse material offers a very good permeability, while the thin fine sediment of the riverbed provides an efficient natural filter for the infiltrating surface water. Exploitation of the approximately 30 km long convenient river section would need a lot of traditional tube or shaft well, since the gravel terrace is not thick enough. Therefore special shaft wells with horizontal screens have been constructed (Figure 8), their capacity is ranging

Figure 8. Bank filtered abstraction in the Szentendre Island, upstream Budapest.

between 10 - 20 thousand m^3/day. Although the travel time is very short, the bank filtered water does not need other treatment than disinfection, which makes the operation relatively cheap. The total capacity of this well field is 600 000 m^3/day, but the actual average abstraction is only 300 000 m^3/day, contributing in 60% to the drinking water supply of Budapest.

Csepel Island, enhanced bank filtration together with artificial recharge for qualitative improvement

The Csepel island can be found downstream Budapest (Figure 9). Here the situation is more sensitive than of the Szentendre Island because of the potential pollution hazard related to Budapest. The geological conditions and hence the majority of the wells are similar to ones in the northern island. But, as an example, the Szigetszentmiklós wellfield is selected. For improvement of the water quality, enhancement of bank filtration and artificial recharge from an infiltration pond are combined. Here, the bank-filtered water is moving through an artificially made bank, constructed of dredged sediment of the Danube-branch. Because of the relatively high content of organic material of the bank material, the water is reduced, consequently high iron and manganese content can occur in the wells. As active protection, recharge ponds have been constructed between the bank and the wellfield (Figure 9). The infiltrated water is pumped from the Danube-branch, providing sufficient dilution of the original bank filtered water. The reed cover of the infiltration ponds has been found very efficient for maintaining infiltration capacity.

Figure 9. Qualitative improvement of bank filtered water with artificial recharge at Szigetszentmiklós.

Borsodszirák, artificial recharge from background ponds

The water quality of the Bódva river in the northern part of the country is good, but the relatively clogged riverbed does not permit an efficient bank filtration. For two reasons construction of a chain of artificial recharge ponds was a feasible solution for this problem; (i) the sandy-gravely river terrace in the background is favourable for intensive artificial recharge and (ii) the quality of the abstracted water can be protected against the pollution from an industrial dumping site (Figure 10). The capacity of the well is 20,000 m^3/day; around 85% of the water originates from the recharge ponds.

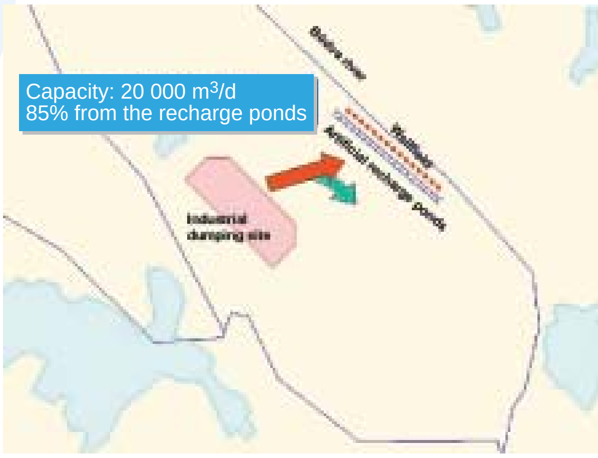


Figure 10. Artificial recharge from background recharge ponds at Borsodszirák.

5 Conclusions

To satisfy the sustainable future water demand a new strategic approach of groundwater management is needed in regions where the actual level of use shows the signs of overexploitation and in areas where the climate change can cause critical situation. Measures should be in harmony with the EU-Water Framework Directive.

As part of the strategy, the increasing exploitation of the bank filtered water resources can provide long-term security for drinking water supply and can decrease the actual high pressure on available resources in porous aquifers in the eastern part of the country.

In areas where excess water and droughts occur in succession, the surplus water during the winter half year should be collected and infiltrated in areas with permeable covering layer, so that this water can be used during summer for irrigation. This solution would be in harmony with the intention for restoring the natural water conditions, i.e. the excess water is used in the area instead of being drained out of the catchment. Under Hungarian circumstances artificial recharge would not be a favourable solution at regional scale, but for solving local water scarcity and to mitigate the harmful impact of human activities it is a promising solution. Irrigation has no priority among water users, at regional scale the water resources are no limiting factor for sustainable developments and there are numerous groundwater dependent ecosystems.
Local water demand for agricultural activities in settlements and in their surroundings

can be partially satisfied from infiltrated sewage water, after appropriate treatment or by applying environmental friendly small scale technologies. Beside the favourable closure of the water cycle, this solution can decrease the thread on the surface water quality from the discharge of untreated sewage water.

As important principle of the general water management strategy, the emphazise on meeting short-term demands should replaced by seeking long term sustainable solutions, therefore water management is now going to be integrated with land use management, environmental management and nature conservation. Economic and social aspects (will) have strong influence on the decisions. Stakeholders participation, open planning procedure for land development and river basin management plans justify and legitimate this decisions.

All measures suitable to decrease the impact of the extremities should be favourably treated. From that point of view the enhancement of recharge of groundwater will be an important tool. In case of protection and exploitation of bank filtered water resources the present role of the state is essential. In concern of recharge enhancement for agricultural purpose the regional and/or local levels should take the initiative. However, the state should promote this kind of development by demonstrating the utility through pilot projects and by subsidising the implementation, especially if the solution contributes to meet general environmental, social and economic objectives.

6 State of the art of artificial recharge through well injection in Mexico

Authors Felipe Arreguín-Cortés and Rubén Chávez-Guillén

Abstract

Because more than half of its territory is dominated by arid and semi-arid climatic conditions, groundwater constitutes an essential resource for development in Mexico. The total groundwater abstraction has been estimated at 28,000 million cubic meters per year (Mm3/a). Agriculture uses 71% of that volume, whereas urban and industrial areas consume 26%. The urban population constitutes of 65% of total inhabitants in Mexico (100 millions). For example, 21 million people live in the Metropolitan Area of Mexico City. Mexican Cities consume 7 600 Mm^3/a and groundwater constitutes two thirds of supply. More than 100 regional aquifers are over-exploited with a yearly abstraction of 5 400 Mm^3/a from storage and the resulting environmental consequences during the last 4 decades. Several corrective strategies to overcome these problems, such as water-demand management, water preservation, water-efficient use, public participation, and artificial recharge have been implemented in main basins. Mexico is facing a severe drought lasting seven years with a reduction in streamflow and aquifer recharge. Drought is considered as a natural cycling condition resulting from gradual changes in climate observed during last years. However, frequent and longer severe droughts are expected to occur, reducing surface-water availability and increasing groundwater demand. Due to the importance of preserving and increasing water storage in the subsurface, this article discusses groundwater recharge potential and obstacles in Mexico, emphasizing technical, legal, social, and economical issues.

1 Introduction

The large water reserve stored underground is an essential resource for human activities. It is a unique permanent supply for dry regions and a valuable additional source complementing seasonal variations of precipitation in humid zones. Wise management of groundwater reserve must consider limitations imposed by its slow renovation and physical, economical, and environmental restrictions. It should provide flexible use avoiding destructive over-exploitation. Groundwater reserve is getting a prime relevance, as severe and prolonged droughts are likely to occur in different zones on earth due to observed global climate changes. Artificial recharge is an alternative to increase and preserve water storage preventing a reduction on precipitation and surface water associated to climate global change. This article focuses on groundwater reserve in Mexico describing its reduction by over-exploitation, and its important role regarding country's development. Strategies for water reserve preservation and possibilities and obstacles for applying artificial recharge are also presented.

2 Groundwater in Mexico: general scope

Current state

Groundwater constitutes an essential resource for development in Mexico, since more than a half of its territory is dominated by arid and semi-arid climatic conditions (Figure 1).

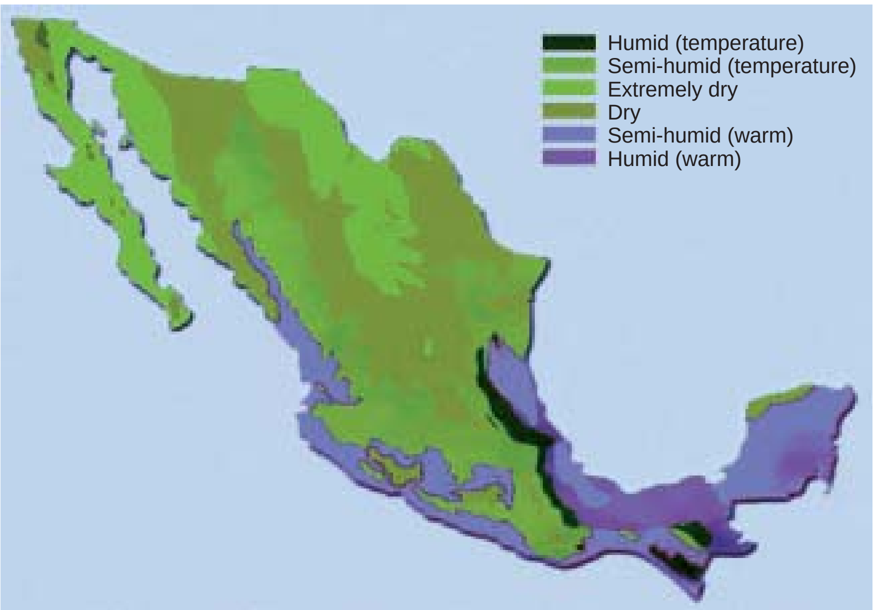


Figure 1. Climates in Mexico.

Current the total groundwater abstraction amounts to 28 000 million cubic meters per year (Mm^3/a). Agriculture uses 71% of that volume; cities – totalling 55 millions of inhabitants, consume 20%; industries use 6%, and rural population

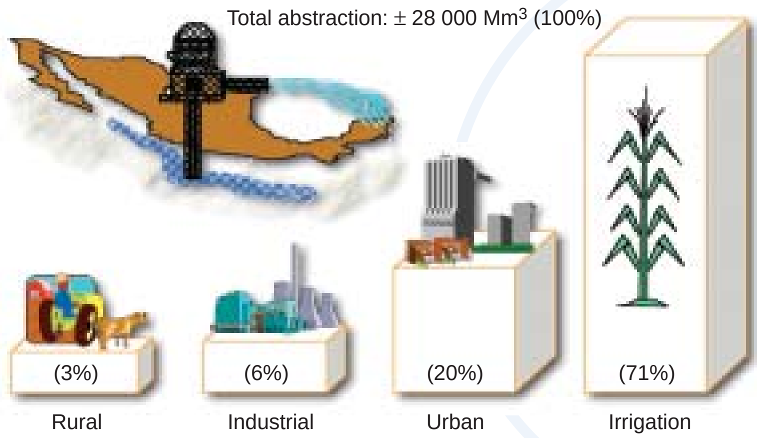


Figure 2. Groundwater abstraction and use in Mexico.

is in charge of the 3% (Figure 2). There are 100 main cities concentrating 65% of total inhabitants in Mexico (100 millions). For example, 21 million people live in the Metropolitan Area of Mexico City. Municipal and industrial zones consume 7600 Mm^3/a of fresh water and discharge 6400 Mm^3/a (160 m^3/s) of wastewater. Groundwater constitutes two thirds of total supply. Increasing effluents are used mainly for irrigation purposes, mostly with no previous treatment.

Slow natural renovation of water resources along with an increasing groundwater demand mostly from agriculture has resulted in over-exploitation of almost 100 regional aquifers. The biggest environmental impact was generated during the first decades of over-exploitation (1960's through 80's), resulting in springs disappearing, desiccation of lakes and wetlands, declining base flow, and lost of ecosystems and natural flora. Related effects were: declining well production, higher pumping costs, land subsidence and fracturing, groundwater contamination, salt water intrusion, and strong competition among users.
Many of the most important Mexican cities, including the Metropolitan Zone of Mexico City, depend on water storage from local aquifers for supplying. However, increasing water importation from neighbouring zones or basins has satisfied growing city demand. This alternative brings problems such as higher costs, less water availability, and opposition from rural population for exporting water to cities.

Mexico is facing a severe drought lasting seven years with a reduction in stream flow and aquifer recharge. Consequences of drought are clearly seen in Rio Bravo/ Grande Basin (bordering the US), one of the biggest in Mexico, where mean annual stream flow during 1993-2001 represented only a third part of that for the 1940 - 2001 period (Figure 3). Drought is considered as a natural cycling condition lasting approximately 10 years. However, frequent and longer severe droughts are expected to occur reducing surface-water availability and increasing groundwater demand.

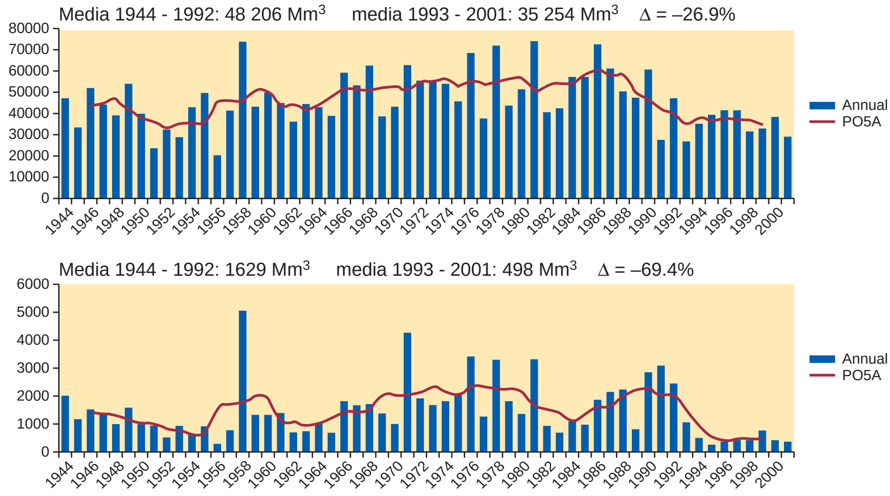


Figure 3. Precipitation and flow of the Rio Grande.

Water use condition threatens progress and development in Mexico with serious consequences in national economics. Sustainable development in country's arid regions will mainly depend on increasing water availability by: i) management of water demand, ii) water reuse, and iii) artificial recharge.

Strategies for sustainable management.

Traditionally, increasing water demand was satisfied by a larger supply through new waterworks. This practice was applied in spite of considerable water losses in pipes and non-efficient water use. As water supply is decreasing along with progressive aquifer over-exploitation, scope has changed into an integrated strategy that emphasizes water demand management involving all users.

Water demand management among different users deserves special care. Some programs have been designed for urban users such as leak detection, water-meter enhancement, and construction of modern water pipes and sewers. Campaigns on efficient water use and penalties on water-law violations have also been implemented. Water recycling and reuse of treated wastewater have been tax-promoted among industrial users for activities that do not require potable water. Modern irrigation projects have also been implemented like using less water-consuming and more productive cultures, restoring irrigation facilities, and applying new technologies (e.g.: plasticulture).

The National Water Law through councils and committees promotes participation of users as main players in water effort. Users and water authority (i.e.: National Water Commission) work together implementing programs on water preservation.

Releasing previous water ownership is promoted to satisfy demand in cities where water availability is not enough. There are several releasing mechanisms. Where urban areas displaced agricultural lands, water rights are exchanged through transference from original farmers to industrial users and city agencies. Some other users, that do not need potable water, transfer his water rights receiving a same amount of treated wastewater. Rights on certain amount of water are also released implementing programs to use less water by enhancement of both crop production and mechanical and hydraulic well efficiency.

As a part of the World-Bank sponsored Program to Modernize Water Management in Mexico (PROMMA), special care have been lately given on monitoring, evaluating, modelling, and sustainable developing of groundwater resources, especially to stabilize over-exploited aquifers. Artificial recharge has been considered to enhance groundwater storage.

3 Groundwater reserve

There is considerable subsurface water storage in Mexico: several basins comprise regional aquifers, some hundred to thousand square kilometres in size and several hundred meters thick. In general, shallow stratigraphy (dozens to some hundred meters in depth) includes coarse-to-fine grained sediments, whereas igneous and sedimentary rocks constitute deeper aquifer horizons.

A recent study on water reserve in the main Mexican aquifers included an estimation of its total size and determinations on storage releases from over-exploitation. It also considered a fraction of groundwater reserve that can be pumped out under different kind of restrictions: physical (e.g.: capacity of modern pumping equipment), economical (e.g.: profitable pumping depth according to water use), and environmental (e.g.: possibility of sea water intrusion, land subsidence or disappearance of natural discharges like springs, base flow, and wetlands).

Results showed that during the last 40 years, 60 000 Mm^3 were taken from groundwater storage in all over the country by aquifer over-exploitation, whereas current release from storage is 5 400 Mm^3/a. Most available groundwater has been stored within the first four hundred meters below the ground surface, in the most permeable aquifers where renovation is more dynamic. There, groundwater has the best quality, and it is economically available. It is considered that there is an important storage up to a reference depth of 400 m. Results on remaining water reserve, however, are being carefully considered, since this type of estimations are mostly optimist and misleading. Groundwater reserves of trillions (1012) cubic meters can give a false impression that there are no supplying problems, even in the long run. Accordingly, the application of preventing and corrective actions for conservation, even for an almost non- renovated resource, would not be necessary.

Uncertainty on groundwater storage estimation is mostly due to a lack of precision during characterization of aquifers several hundreds meters deep, especially in fractured media. Moreover, porosity and permeability decrease with depth due to rock overburden and renovation of water within deep aquifers is so slow that groundwater is considered as ‘fossil’. In this case, long water-rock interactions resulted in an increase on groundwater salinity, not suitable for most common uses. Besides, fossil groundwater has been reserved for more profitable and less demanding uses due to higher pumping costs.

The Mexican experience gained from several cases on aquifer over-exploitation, is self-instructive and valuable to orient groundwater management. It establishes in anyway that groundwater is a valuable resource used to overcome scarcity and both seasonal and yearly variations in precipitation and runoff. On the other hand, this experience warns for generating multiple harmful effects resulting from aquifer over-exploitation. In the long run, harmful effects have produced a non-sustainable destructive condition. For many cases, similar experience has shown that temporal and controlled over-exploitation is possible and even recommended, only when it finishes on time and it is affordable in terms of costs and benefits.

Even its potential size, deep groundwater constitutes a non-renovated resource that presents several limitations for use. It should not be considered as an inexhaustible water source to complete or replace the current water supply from shallow depths.

Deep groundwater is becoming important since it allows a greater flexibility for integrated water management. It will be a key factor for extensive and severe droughts derived from global climatic changes. It is urgent and necessary to implement strategies for managing deep groundwater in order to increase supply and preserve this resource.

4 Artificial recharge: possibilities and obstacles

Isolated artificial recharge projects have been conducted in Mexico in different periods of time. However, spreading of recharge practices has been delayed due to technical difficulties and the fact that it is still possible to take additional water from existing supply facilities. Possibilities and obstacles for application of this methodology in Mexico are discussed below.

Technical issues

Artificial recharge depends on several technical issues: a) sufficient water for recharging purposes; b) good water quality to prevent impairment of native groundwater or feasibility of artificial/natural pre-treatment to avoid contamination; c) land availability for recharging facilities; and d) prompt and easy recovery of recharged water.

Water availability in Mexican arid lands is a limiting factor. Stormy events in some arid lands generate extraordinary runoff that could be used for artificial recharge modifying riverbeds and infiltration basins. In several basins along the Pacific Coast large quantities of water are available from hurricane strokes that generate torrential runoff discharging to the sea with no further use. A recent project considers a combination of artificial recharge and the construction of a subsurface dam to increase groundwater storage, allowing a flexible pumping with no risk of seawater intrusion.

Wastewater from urban and industrial zones constitutes an enormous potential supply for artificial recharge, mainly for its increasing volume and its perennial nature. Wastewater quality, however, represents a main concern: i) treatment is required to prevent contaminant risks and damages to public health, especially when recharged water is intended for human consumption; ii) since wastewater irrigation is a common practice in Mexico with no further regulations, a previous wastewater-ownership release would be required for recharging purposes. There is a huge recharging potential in the Mexico City Basin where effluent flow rate is 40 m^3/s. Large-scale wastewater treatment for reclamation and artificial recharge is considered. However, care must be taken to avoid contamination in a city full of potable-water supplying wells.

Feasibility of joint management involving dams and aquifers has being assessed in humid and semi-humid regions, where exceeding surface water can be used for artificial recharge. It is also possible to collect rainwater for recharging purposes in the same regions. Some projects for urban and industrial development are considering this options at the Metropolitan Zone of Mexico City and other important cities.

Few artificial recharge projects have been conducted in Mexico. Stabilization of over-exploited aquifer, and attenuation of draw down, land subsidence, and seawater intrusion have been their main objectives. Additional objectives will be increase and preserve groundwater storage during extreme dryness conditions derived from global climate change.

Recharge methods comprise surface (infiltration basins and riverbeds) and subsurface application. Surface recharge has greater possibilities in scarce populated zones, whereas it is difficult to achieve in populated cities, where land availability is a major problem. Construction of wells to inject water through saturated/unsaturated zones is becoming popular in those cities.

Legal issues

Mexican water laws require permission from water authority for both artificial recharge and subsurface water disposal. There is a project to formulate a Mexican Official Standard (NOM) on groundwater recharge regulations. Artificial recharge using rain or surface water that has not run over polluted watercourses is not yet regulated. NOM results in national regulation facing a dual reach: i) it should be so strict to difficult its compliance or discourage artificial recharge projects; ii) it should not be so weak to threat public health.

Main NOM objective is to protect aquifer water quality and prevent damage in public health. NOM project is willing to establish guidelines on quality of effluents being recharged, instead of regulating treatment systems or methods for artificial recharge. It establishes quality requirements to be met depending on recharge method (from surface or from subsurface) and potential use of recovered water. It also defines minimal distances between recharge facilities and closest potable wells. If recovered water is intended for potable uses, NOM defines strict water quality criteria and considers subsurface natural treatment as a complementary protection. If final uses are distinct to human consumption, natural treatment is considered to relax water quality requirements for recharge, lowering costs on previous treatment.

NOM considers subsurface environment as a natural treatment plant. There is a tendency to use it through a suitable combination of pre-treatment-natural treatment-post-treatment; according to recharge methodology and final use of recover water. Artificial recharge using wastewater is recommended when recover water is not used for potable purposes. However, extreme care must be taken when wastewater recharge is intended for human consumption to avoid risks in public health. In such a case, some issues are required: basic studies, tertiary/advanced pre-treatment, careful monitoring, suitable distance among recharge sites and recovering wells, etc. Sooner or later, wastewater recharge will be necessary in some northern Mexican basins, if there are no other reliable options.

Social and economical issues

Mexican water users are not yet familiar with artificial recharge practices. It is possible to face scepticism's and social resistance. For example, surface water recharge is not widely accepted by users that do not understand the advantages of subsurface as a treatment plant or as storage. According to some of them, it does not make sense to infiltrate water into the ground and then recover it later.

Greater social opposition can be expected for wastewater recharge when there is a possibility of using recovered water directly or incidentally for potable purposes. Resistance is mainly due to 'green groups' that adopt a strict position – sometimes justified, defending human health. They can ask for standards that may be difficult to achieve. Sometimes, they forget that incidental recharge associated to country development may generate pollution which control is difficult.

Artificial recharge involves high costs derived from preliminary studies, design, construction, operation, maintenance, and monitoring of systems. Small-scale application from industrial and municipal users can be achieved, if they can obtain some benefits. In general, small farmers cannot support artificial recharge. They are numerous and their water consumption is high. Private recharge projects in small scale are appreciated and joint efforts can bring local benefits for aquifers. Larger recharge projects to create or increase available water storage for future use are only feasible if government and organized users support them. This possibility is being addressed by local Groundwater Technical Committees (COTAS) for over-exploited aquifers, as a strategy for sustainable management.

5 Study case: Pilot project of artificial aquifer recharge at the Comarca Lagunera aquifer, Coahuila

Introduction

The Comarca Lagunera Region of northern Mexico is one of the principal agricultural areas. Water supply is based upon control of the discharge of the rivers which drain into the region, Nazas River and Aguanaval River, for irrigation, and some 3500 boreholes which abstract groundwater from the Comarca Lagunera aquifer, for agricultural, domestic and industrial use.

The rivers flowed into the internal drainage basin of the Comarca Lagunera, until the construction of dams. Under normal conditions the total controlled discharge of the river is now fed into a system of irrigation channels, and only in flood events do its natural riverbed carry flow downstream of the urban area. The agricultural development has increased rapidly since 1940's resulting in a major imbalance between abstraction from, and recharge to the aquifer. At the present, it is estimated that abstraction is at least three times greater than the recharge. The result of this overexploitation has been a significant decline in the level of the piezometric surface and decline in groundwater quality. The main concern is the occurrence of arsenic in groundwater at concentration well above the WHO standard for domestic use of 0.05 mg/l. The occurrence of arsenic in the groundwater has been locally identified as a major threat to the water supply of the region.

Artificial groundwater recharge constitutes an alternative for overcome water table drawdowns using streamflow, and at the same time to protect public wells from high arsenic concentration. In order to increase the storage capacity and control the arsenic groundwater deterioration a pilot artificial recharge project was carried out at the area. The main object was to assess the infiltration capacity of the unsaturated zone and the water table response to artificial recharge using surface water into a riverbed.

Methods

A recharge sand basin was adapted near to the Nazas Riverbed, in Torreon City, covering an area of 130 000 m^2 with a storage capacity of 197 386 m^3. Waterworks were implemented to convey surface water from Zarco dam through Sacramento irrigation channel to the recharge basin. Two monitoring wells were drilled for observing local water-table responses during recharge. Monitoring well No.1 was constructed 30m deep and located 200m down gradient from the centre of the recharge basin, whereas monitoring well No. 2 was constructed 50 m deep and placed 500 m down gradient from the basin. Twelve pre-existing well were conditioned for additional water table observation during the recharge operation covering a monitoring radio of 3 km. At the beginning of the experiment, surface water was conveyed for basin spreading every 8 - 10 days. However, during the last 30 days, the frequency of spreading was less than a week. Water quality was defined in terms of TDS concentration of 200 mg/l and 40 mg/l of TSS and showed no arsenic content.

Results and discussion

Surface water derivation starts on May and finished on August 2000. A total volume of 5.2 Millions of cubic meters (Mm^3) was conveyed through Sacramento channel. From this volume, 0.2 Mm3 was evaporated and 5.0 Mm^3 infiltrated to the subsurface. Depths to water table varied from 0.51 m through 3.47 m at the well No.1 and from 22.70 through 21.70 m at the well No. 2, respectively. Water infiltration capacity was reduced from 2.4 (m/d) to 0.116 (m/d) due to clogging phenomena. After 3.7 Mm^3 of water, with a TDS of 40 mg/l, released over a 130 000 m^2 area, a sediment load of around 0.114 g/cm^2, was estimated to create a thin cover layer over the infiltration basin. The main areas affected by the clogging bed were the deep ones.

Analysis on variations of water table depth along with information regarding water quality and hydrogeological conditions suggest that recharged water infiltrates following a ‘stepping path’ controlled by an irregularly-distributed interbedding of shale and fine and coarse sediments. At the beginning of recharging events, the groundwater flow in the vadose zone had a main vertical component. In contrast, by the end of the experiment, when the frequency of surface water application was less than a week, the horizontal component was the main driving force. An upper groundwater flow near to the subsurface was observed falling down like a cascade inside the casing of monitoring well No. 2.

The nature of stepping flow and calculations on flow timing, along with the recharge volume required to saturate the total volume beneath the recharge basin, show that is not likely that the wetting front has reached the regional water table located around 120 m below ground surface. It would require a larger volume, at least three times greater than that used during recharge experiments to reach the regional water table at recharge basin site. In this case, continuing artificial recharge should be extended for more than six months. A 'piston effect' produced by the displacement of a pre-existing waterfront by recharging unsaturated flow is also considered. Previous waterfront resulted from precipitation, runoff, and leakage from irrigation channel. Arrival of this waterfront at regional water table helped by artificial recharge is a strong possibility.

Conclusions and Recommendations

Artificial recharge for public supply use by using surface water is feasible for preserving groundwater quality and increasing storage at the Comarca Lagunera Aquifer. In order to improve the actual operation recharge system the following recommendations should be implemented: i) to built a new hydraulics derivation structures for controlling surface water delivery from Sacramento Channel to recharge basins; ii) to release a maximum volume of 500 000 m^3 of surface water per week to avoid basin spills; iii) to construct parallel recharge basin, like sedimentation basins, to reduce clogging effect, and iv) to construct absorption wells at the unsaturated zone, 20 m deep maximum, and > 12″ in diameter at recharge basin No. 2 to avoid low-hydraulic conductivity horizons and decrease arrival times at regional water table.

6 Conclusions and recommendations

Groundwater reserve is a strategically valuable resource for development, especially in dry regions. Its magnitude, permanence and ample spatial distribution compensate scarcity and temporal variations in precipitation runoff and aquifer recharge. It confers a greater flexibility on integrated water management. Non-controlled over-groundwater exploitation generates several pernicious effects resulting in a non-sustainable destructive condition in the long run. Controlled temporal over-exploitation is possible and even recommended, only when it finishes on time and it is affordable in terms of costs and benefits. Rational management must consider that groundwater reserve is large, but it is not being renovated. Additionally, its exploitation faces physical, economical and environmental restrictions, and an exact determination of its magnitude decreases with depth. It will become significant with severe droughts resulting from global climatic changes. It is important and urgent to implement management strategies to increase and preserve groundwater reserve for primary uses (e.g.: drinking). Strategies should include artificial recharge among them.

Studies about plausibility and pilot projects both on artificial recharge are strongly recommended. The main aspects to be considered are: detailed hydrogeology of study area (i.e.: soil, vadose and saturated zones); water quality of both recharge water and native groundwater; evaluation of suitable recharge methods; predictions about further effects using both groundwater and hydrogeochemical modelling. Possibilities on wastewater reclamation through artificial recharge and further recovery for potable purposes should be investigated, especially in cases of scarcity and lack of complementary supply.

7 Coping with water scarcity: a case history from Oman

Authors Bela Petry, Jac van der Gun and Petru Boeriu

Abstract

Water scarcity in different regions of the world is well recognized as a fundamental problem, which requires full attention from all sectors of society to achieve the objectives of satisfying primary needs and a sustainable social and economic development. The Arab World mainly located in arid, hyper arid and semi arid climates is prominent among the regions in which the problems of scarcity are most acute. According to the World Bank, [*7*], 60% of the 20 countries most affected by water scarcity are located in the Arab World.

In order to cope with water scarcity, a wide range of conventional and unconventional solutions may play a role in the Arab World, including supply oriented measures, demand management measures and water augmentation measures. This paper focuses on dam type schemes for the purpose of augmentation of regional water resources. An assessment of their scope in different regions of the Sultanate of Oman is summarized below. The methodology used and some of the conclusions drawn may be applicable to other countries of the Arab World as well.

1 Introduction

At the end of the 20th century it becomes very clear that fresh water resources, their wise use and conservation possibly represent the most important concern for human societies in numerous parts of the World for the next future. Present date assessments by FAO, UNESCO, World Bank [*3*], [*4*], [*9*], etc., all concur in presenting a relatively critical prospective of the future and underline the difficulties to achieve the satisfaction of fundamental water resources needs and well balanced development in many areas of the world.

In some countries situated in arid regions, sustainable water availability per capita is already below the level that would allow enough food to be grown locally to feed the population. In some of the countries, policies call for enough food to be produced locally for the purpose of self reliance and for economic reasons. These policies have in some cases resulted in the exploitation of fossil water, a non-renewable resource, for the production of low-value food crops. It also generally results in domestic food production at a higher cost than international market prices, thus decreasing the food security of the lower-income sector of the population or requiring government subsidies.

The management of scarce water resources requires, possibly more than ever before, strong links between the water sector, national economic policies and international co-operation with a main target set on securing self and reliable supply of drinking water and food, seen as the most important needs of societies involved.

2 Water scarcity in the Arab Region

Most of the Arab World is located in arid and semi arid regions and is one of the driest areas of the world. The term 'arid and semiarid regions' encompasses a wide range of climatic and physical diversity, including areas with substantial differences in characteristics, as micro-climates.

A characteristic feature of the zones in question is an often observed disconnection between surface and subsurface hydrology. Significant recharge of groundwater by infiltration occurs only after extreme rainfall events, although there are several huge fossil aquifers that originate from earlier, more humid climatic regimes (e.g., the Great Artesian Basin in Australia and the Saharan aquifers).

The water potential of the region is made up from renewable surface water averaging around 338 billion m^3/year, groundwater aquifers with a potential of around 7734 billion m^3 of fossil water at depth ranging from 1000 to 2000 m while renewable recharge for the whole region is estimated at 42 billion m^3/year.

In several countries of the region renewable freshwater will barely cover basic human needs into the next century. Within the period 1960 to 2025 per capita renewable supplies in Arab Countries will have fallen from 3,430 m^3 to 667 m^3 per year which represents 30% of the estimate for Asia, 25% of that for Africa and 15% of the estimate for the World, see table 1 (Source: World Bank, [9]).

Apart from physical shortage and the widening water deficit, the region is suffering from many water shortage related consequences. Among these the most stringent are:

- Irrigation accounts for some 80% of total withdrawals although demand in urban areas is growing rapidly, Figure 1;
- There is a strong on going urbanization process. By the year 2025 about 75% of total population will be living in urban centres (60% today);
- Domestic water use is relatively low in many parts of the region. It is estimated that one third of the total population of the region has no access to safe water (Arab Fund 1992, [6]);
- Major surface water resources in the region are shared between countries lying on both within and beyond the region. The most significant river basins are those of Jordan, Nile and Euphrates/Tigris, all of which are subject to contentious riparian issues.
- Large aquifers underlie North Africa and the Arabian Peninsula. Though costly to develop, they could be shared by several countries but exploitation strategies still need to be developed and agreement on abstractions will be difficult to achieve;
- The potential for storage and diversion projects is limited and political objections to inter basin water transfers may prove insurmountable even if formidable financing and implementation problems could be overcome;

Table 1. Water availability in selected Arab Countries, (Source: [9]).

Country	Net annual renewable resources in BCM	Renewable resources per capita, in m^3/year 1960	1990	2025
Algeria	18.40	1 704	737	354
Bahrain	n.a.			
Egypt	58.30	2 251	1 112	645
Iraq	100.00	14 706	5 285	2 000
Jordan	0.86	529	224	91
Lebanon	3.94	2 000	1 407	809
Lybia	0.70	538	154	55
Morocco	29.70	2 560	1 185	651
UAE	0.30	3 000	189	113
Tunisia	4.35	1 036	532	319
Syria	5.50	1 196	439	161
Saudi Arabia	2.20	537	156	49
Oman	2.00	4 000	1333	421
Yemen	2.50	481	214	72
Africa	4 184	14 884	6 516	2 620
Asia	10 485	6 290	3 368	2 134
World	40 673	13 471	7 685	4 783

- Many countries are already strongly dependent on groundwater and face severe problems of depletion;
- Non conventional sources include wastewater treatment and reuse, and desalinization. They are invariably more expensive than traditional sources.

In the face of the challenges represented by seasonal water shortages, flow fluctuations, drought spells and the increasing demands for water for food production, the region witnessed different forms of interventions. These range from rainfall harvesting and diversion techniques to larger impoundment's in major river basins to improve water availability during the dry periods and even pluri-annual storage to mitigate the recurrent drought risks over the years.

The urgency of solutions to water related problems are increasingly recognized worldwide and there is a growing consensus on the principles that should guide action in this area. Key principles, which should guide national water strategies,

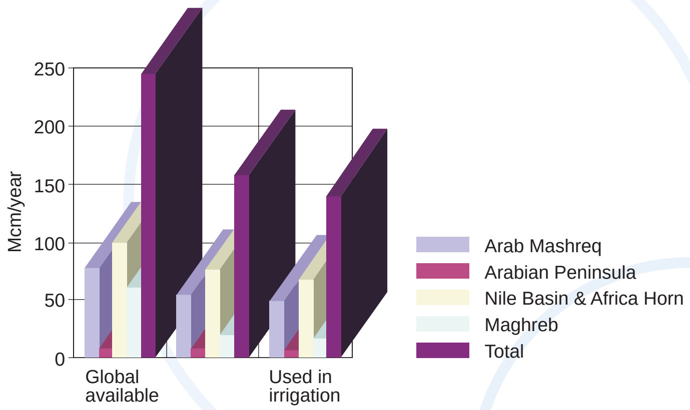


Figure 1. Water availability and utilization

include among others the following:
– Full attention should be given to both supply and demand management practices and measures;
– Demand management and water conservation should be promoted through both economic and non economic measures (licensing, incentives, awareness raising, capacity building, changes in crops, etc.);
– Sustainability of the use of water resources, in a broad context.

Water withdrawals are already exceeding renewable yields in different regions of the Arab World or are expected to exceed them in the short-term future (e.g. Oman, Egypt, Jordan, Yemen, etc.). Alternative water development and management strategies, including all their technical, economic, environmental and institutional aspects, should be systematically evaluated, in the endeavour to cope with increasing water scarcity. An integrated approach incorporating the conjunctive use of wadi flows and groundwater in a basin wide context should be adopted. Dam schemes for storage, groundwater recharge or diversion purposes may offer effective and substantial contributions to the alleviation of water scarcity, in particular in the middle and lower reaches of major wadis.

Hence, they should play a prominent role in integrated water resources development and management strategies, but their potential seems not yet fully recognized and explored in all countries. There is a need to better explore the scope of such schemes in the context of integrated water management in water scarce areas. An assessment carried out in Oman a few years ago is presented bellow as an illustrative example.

3 A case study: Oman

Introduction

Oman is one of the countries located on the Arabian Peninsula having scarce renewable water resources. It ranks among the 20 countries in the World facing severe water scarcity. Oman is divided in regions of very distinct topography and geographic features, Figure 2. The climate is predominantly hot and arid. Mean annual precipitation is 100 mm or less along the coast and in the interior of

Figure 2. Administrative regions of Oman

Northern Oman but higher (200 - 300 mm) at greater elevation in the mountainous regions of the country and very low (less than 50 mm) in central Oman.

The total population of the Sultanate is 1.5 million at present, with about 60% concentrated in the capital area. Population growth in the different regions and in the capital area is shown in Figures 3 and 4, respectively.

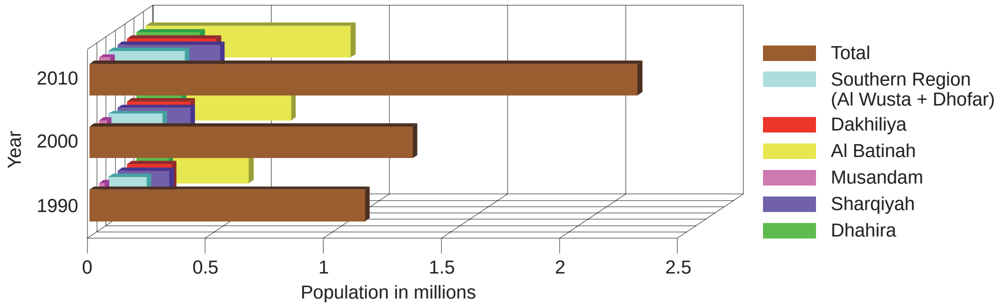


Figure 3. Population projections per regions

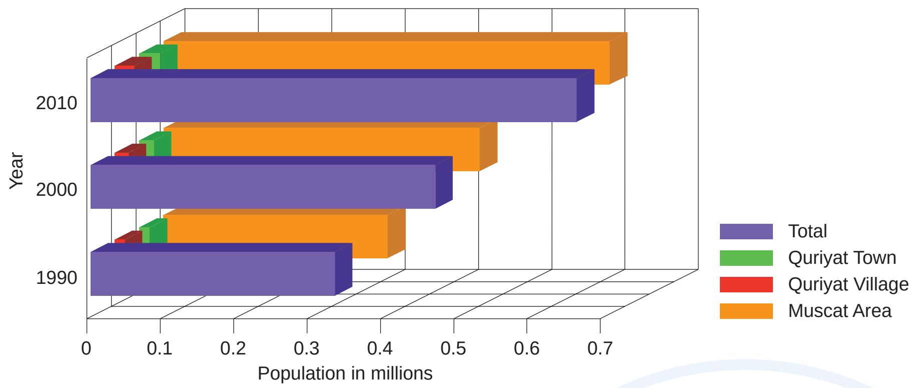


Figure 4. Population projections in the capital area

An assessment of the water demands, Figure 5, shows the strongly increasing demands prognosis in different areas of the country.

The overall figures of the regions may disguise considerable differences between individual catchments particularly in the interior of Northern Oman. Important conclusions from assessing the water demands are:
- For 1990 more than half of the nation wide water demands and around half of the renewable water resources correspond to the Batinah and Capital areas. This proportion is likely to remain the same by year 2010;
- Average regional deficits of renewable water were about 28%, in 1990. These deficits were covered by groundwater mining, unsustainable in the long term, [*7*];
- The regional water totals do not show the discrepancies between available water and water demands that occur locally and which are much more serious than suggested by the Figure 6, [*7*].

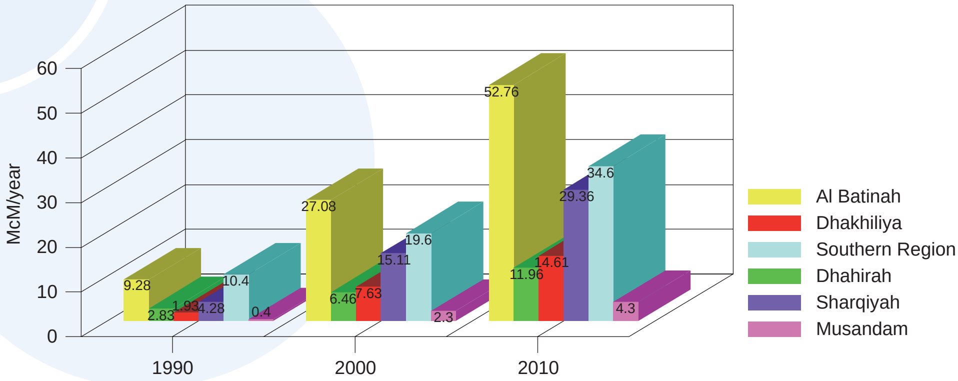


Figure 5. Water demands

Considerable efforts are being oriented in Oman towards possible solutions to the severe deficit of water resources in the country and its different regions. Such solutions will doubtlessly have to consider the full range of water resource management capabilities including therefore, in addition to normal practices, less conventional measures such as demand management, development of artificial groundwater recharge schemes, water recycling, diversion schemes, water harvesting and even desalinization of sea water. In this array of possibilities measures to increase the use of flush flood discharges of the wadis are certainly of relatively great importance in view of their good potential. Such measures include artificial groundwater recharge, diversion schemes for spate irrigation and surface storage schemes, which were the scope of an assessment carried out in 1995, [6]. The methodology and the outcomes of the assessment are summarized below.

Assessment of needs for water conservation schemes

Figure 6 presents the need for water conservation per region, on the basis of a number of indicators. An overall score for the need, based on selected indicators for the year 1990 is determined and given in the figure. Among the indicators used, the most important are the ratio between the regional water demand (use) U, and the rate of renewal of the regional water resources, R.

Other indicators such as the need for salinity control, for flood control and for water supply are also considered in determining the overall score. The ratings are combined on an ordinal scale ranging from 0 to 3, mainly based on the U/R ratio with:

– score 0 for $U/R < 0.95$
– score 1 for $0.95 \leq U/R \leq 1.15$
– score 2 for $1.15 \leq U/R \leq 1.35$
– score 3 for $U/R > 1.35$

If other indicators are significant then the overall score is upgraded to the next class.

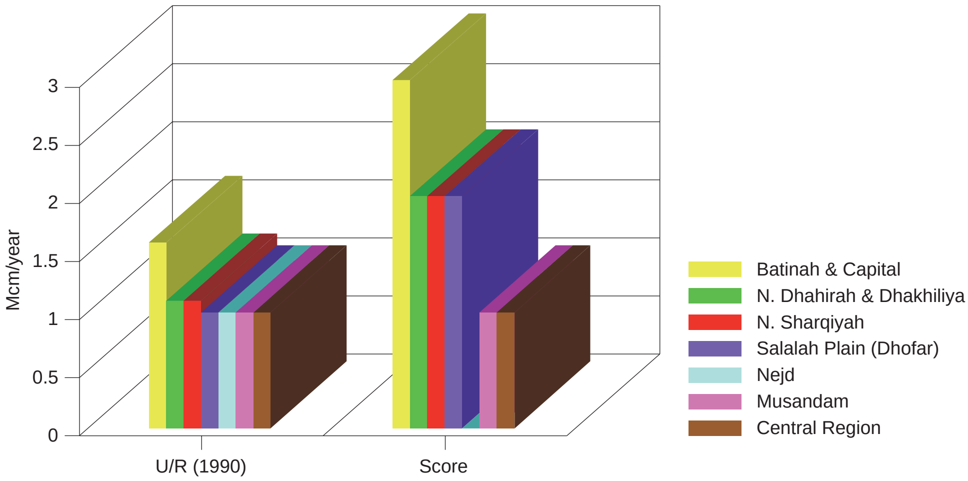


Figure 6. Need for water conservation schemes

The result of assessment shows that the need for water conservation schemes is greatest in the Batinah & Capital Area. Second in urgency are the Interior Catchments of Northern Dhahira and Dakhiliyah (Interior Plains), the Northern Shaqiyah and Salalah Plain.

The potential for recharge dam schemes

The potential for recharge dam schemes in Oman is shown in figure 7.
The main parameters considered for determining an overall score were:
- Sources of surface water: wadis, floods, frequency of floods, annual runoff volume;
- Surface water lost: Only if under present conditions significant volumes of fresh water are lost to the sea or to areas beyond the zones where it is mostly needed, then a recharge scheme would make sense. In other cases a scheme would lack a relevant function;
- Target aquifer: storage capacity, permeability characteristics, groundwater quality;
- Suitable dam sites: topography, sites of relevant wadis, local building materials, economic feasibility.

The overall score is synthesis of the scores on the indicators mentioned above ranging from 0 to 3:
- 0 for no potential
- 3 for good potential

The main remarks that can be drawn by analyzing the potential for recharge dam schemes are:
- The Batinah & Capital Area is rated as the region with the best potential for recharge dam schemes;
- These schemes should be sited on the Batinah Plain where the most important aquifer system of the country is present, wadi regimes are favourable and the functionality of the schemes – interception of surface water loss – is clear;

– According to the National Water Master Plan (1991) recharge schemes on all relevant wadis in the Batinah Plain may have a total impact of on average some 33 million m^3 of water saved per year;

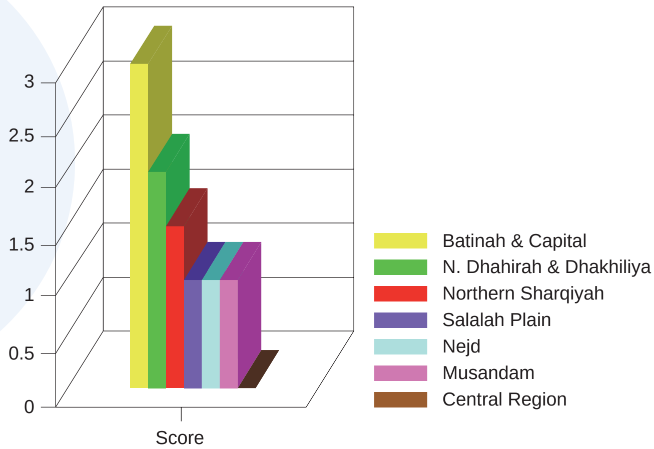


Figure 7. Potential for recharge dam schemes

– The alluvial plains along the southern and western foothills of the Northern Oman Mountain – in Dhahira, Dakhiliyah and Sharqiyah districts – rank second best in potential. They are traversed by many wadis with good yields, but the aquifer systems are generally less favourable:
  - thin and poorly developed in interfluvial zones;
  - zones of fresh groundwater are of limited extent;
  - upstream - downstream interactions may be much more complex than on the Batinah Plain;
– There is very low potential for recharge schemes in the Central Region.

The potential for storage dam water conservation schemes

Site requirements for storage dams are different from those for recharge dams. The main parameters coming into consideration when a storage dam water conservation scheme is to be selected are:

– The geological conditions are strongly limiting the location of a reservoir created by a dam: a typical storage dam should have impermeable reservoir bottom and sides in order to prevent leakage losses;
– The impoundment surface is a permanent one and therefore exposed in hot climate areas to high evaporation rates. Consequently the ratio between the wet surface of the reservoir and the stored volume should be kept as small as possible;
– The dam impoundment schemes are effective only under special conditions, e.g., catchments where streams discharge directly into the sea without traversing zones of significant permeability or zones where the wadis loose water to a formation from which it can not be recovered due to technical, economic or water quality constraints.

The result of the assessment of the potential of dam storage sites in Oman is given in figure 8. The overall score is determined on the basis of the indicators given. The main conclusions may be summarized as follows:

– The potential of storage dams as effective instruments to conserve water on a regional scale is less than that of recharge dams;

- The overall picture is different from region to region. For example the potential of a storage dam in Wadi Dayqah – estimated to save 15 million m^3 water per year – makes the potential of storage dams in the Muscat area (although it might be one only) more important than of recharge dams;
- It is possible that for the Central Region and Nejd storage dams will prove to be more effective for water conservation than recharge schemes;
- Comparison of the figures shows rather strongly correlation between the regional potential for recharge schemes and that for storage dam schemes with Batinah & Capital Area as the most promising region. This result mainly from the relative abundance of surface water sources, compared to those in other regions.

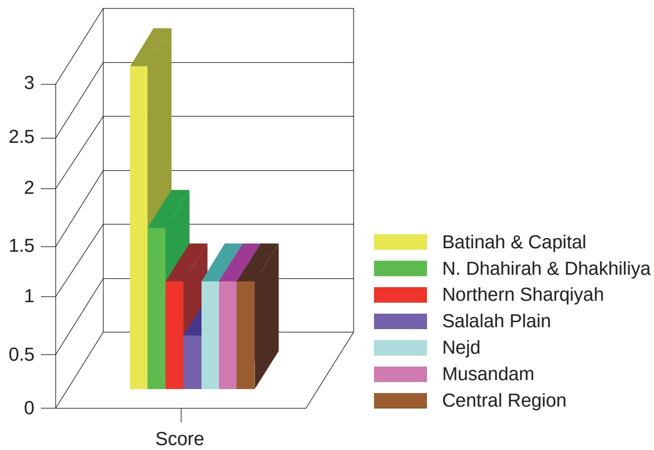


Figure 8. Potential for storage dam schemes

The potential for diversion dam schemes

Only diversion dams constructed for spate irrigation were considered in this assessment. This type of construction is used to divert occasional floods from a wadi toward irrigated fields or toward recharge fields commonly consists of an earthen or gravel deflector and cross dams in the wadi. They are effective only if the soils are well developed and deep with large moisture holding capacity and if the crops are rooting deeply.

The assessment of the potential spate irrigation for the conservation of water in different regions of Oman is shown in figure 9.
Most of the indicators are similar to those of the storage dams. A major difference is the site requirements for spate irrigation projects: a critical requirement for spate irrigation is that suitable agricultural lands are located along a wadi reach where floods are rather frequent and in such a topographic position that simple dams can divert floods which are subsequently conveyed to the fields entirely by gravity.

Spate irrigation is attractive if suitable land is available and if the frequency of floods is at least a few floods per season. Due to the high interannual variability of runoff and the absence of buffers in time, the area actually irrigated may vary considerably from season to season and from year to year. This variation can be reduced if spate irrigation schemes are operated in conjunction with recharge schemes and/or if groundwater wells are used to supply water during relatively dry periods or seasons.

The later form of conjunctive use of surface water and groundwater can be economically very efficient.

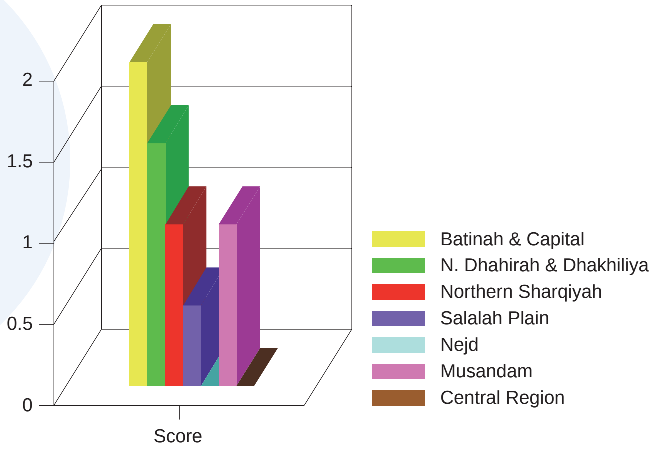


Figure 9. Potential for diversion dam schemes

The patterns of potential for diversion dam schemes are rather similar to those of recharge schemes. Main remarks are:

– The Batinah Plain & Capital Area scores best, followed by the Interior Plains;
– Absence and limited thickness of well developed soils at suitable locations along the wadis may be a bottle neck;
– A field investigation of soils should be considered;
– Spate irrigation schemes on the Salalah Plain seems to be an option, but additional investigations are still needed;
– Combined schemes of spate irrigation and groundwater irrigation should be studied.

Conclusions

By multiplying the scores obtained for the need for water with those for the potential of the different categories of schemes considered a final score can be determined. The results of this exercise are given in figure 10. These scores express the relative scope for different categories of schemes as instruments in water conservation in the different regions of Oman.

The score range from 0 (no scope) to 9 (good scope).

The main findings on the scope for dam schemes are:

– The best prospects for water conservation by dam schemes are found in the northern part of the Sultanate;
– According to this evaluation the Batinah/Capital Area has the best scope for water conservation by dam schemes. It is followed by the Interior Catchments of Northern Dhahira and Dakhiliyah and by Northern Sharqiyah;
– As far as recharge dams schemes are concerned this is in complete agreement with the preferences shown in the activities of the Dam Department of the Ministry of Water Resources.

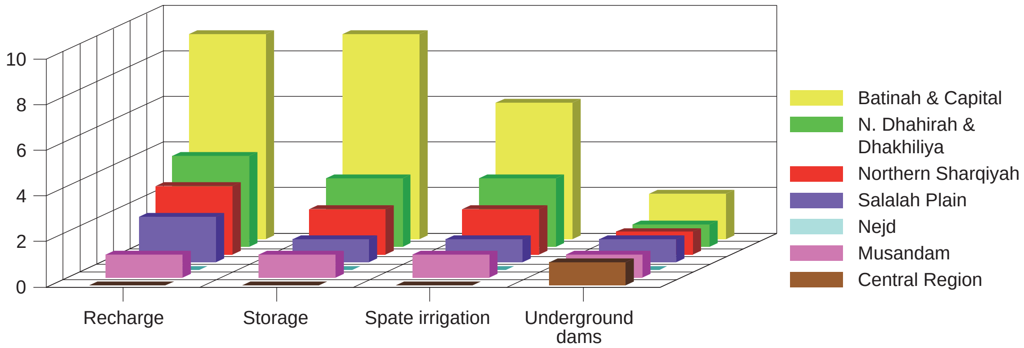


Figure 10. **Water conservation schemes in Oman**

It should be mentioned that this rating of relative scope applied in this approach is subject to some restrictions. Among these, the most important ones are:

- It may be possible that certain schemes (e.g. storage dam schemes) are expected to have little or no contribution to water conservation but still could be extremely useful for example as a means for local development of water;
- The whole assessment is on regional scale. Consequently it gives a low rating to those schemes that are expected to have an insignificant impact on the regional water balances. However, these schemes may have important local impacts;
- A large number of local small schemes may produce a significant result at the regional scale;
- This analysis does not take in account economic constraints.

Finally, the importance of possible combinations of water conservation schemes should be underlined. A storage dam constructed for storing and supplying water directly to a user may also contribute to aquifer replenishment for example. In the same way spate irrigation systems are primarily designed to irrigate agricultural lands but as a side effect they may enhance groundwater recharge considerably due to downward percolation of infiltrated water. Therefore in a regional planning it is important to analyze possible combinations of dams that are complementary to each other or to consider single dam schemes that combine different functions such as surface and subsurface storage or water supply and recharge [*7*].

4 Concluding remarks

Water conservation schemes using intermittent flood regimes of wadis may well contribute to the alleviation of water scarcity in arid and semi arid regions of the world, such as illustrated in the case of Oman.

The possibilities of developing such schemes should be systematically considered at the level of regional water resources planning and not only as localized solutions to the problem of water shortage.

Assessment of needs and potentials for such schemes at regional level are seen as an important component of water resources planning, following a methodology similar to the one used for the case study presented in this paper.

References

1. ***Khouri J., Salih A. et al.***: Rainfall Water Management in the Arabic Region – ROSTAS, Cairo, 1995
2. ***FAO***: Water Resources of African Countries – FAO Publication, Rome, 1996
3. ***FAO***: Food Production – AO Publication, Rome, 1996
4. ***Lloyd, J. W.***: The Reality of Recharge in Arid and Semi Arid Areas – International Conference on Water Resources Management in Arid Countries, Muscat, 1995
5. ***Mageed, Y.A.***: Planning Water Resources Development in Arid Zones – Proceedings of the International Conference on Water Resources Management in Arid Countries, Muscat, 1995
6. ***Petry, B., Gun J. van der***: Future of Recharge and Similar Schemes in Oman – Report, submitted to the Ministry of Water Resources of the Sultanate of Oman by Euroconsult, 1995
7. ***Petry, B., Boeriu P.***: Hydraulic Structures for Water Harvesting Schemes – FAO 1998 (in press)
8. ***The World Bank***: A Strategy for Managing Water in the Middle East and North Africa – World Bank Publication, Washington, D.C., 1994
9. ***Wheater, H.S.***: Water Resources Management under Arid Conditions – Water Resources Integrated Management in the Arab Region, Amman, December 1995

8 Infiltration basins and other recharge systems in Southern Africa

Authors Gideon Tredoux, E C Murray & L C Cavé

Abstract

Management of aquifer recharge (MAR) is known in Southern Africa and studies over the past three decades have led to the construction of three such schemes. Of these, the Atlantis infiltration scheme has been in operation for over two decades. Most of the Southern African subcontinent is underlain by fractured hard rock formations and thus borehole injection is the most appropriate MAR technique. The Windhoek pilot scale injection runs proved to be very successful, with high injection rates, and a scheme consisting of three implementation phases is underway. In contrast, small-scale injection systems were developed both in South Africa and Namibia, proving the feasibility of the technique for improving the sustainability of rural water supply. MAR is an essential tool in the semiarid to arid environment provided recharge water and suitable aquifers are available. The Atlantis MAR experience is presented as a case study.

1 Introduction

Presently, full scale artificial recharge schemes for augmenting primary aquifers are in operation at Atlantis in the Western Cape and in the Omaruru Delta in Namibia confirming the viability of the technique for such aquifers. In Botswana the concept of artificial recharge was tested at Maun in the Okavango Delta for augmenting the groundwater supplies to the town.

An initial assessment and feasibility study of artificial recharge schemes in Southern Africa, identified the need for testing the concept in secondary aquifers, and in particular, fractured, hard-rock environments (Murray & Tredoux, 1998). Artificial recharge to South African aquifers is not a new concept as farmers in many parts of Southern Africa have constructed earth dams for increasing the recharge and thus augmenting their borehole supplies. Generally, no scientific information is available on the effectiveness of such artificial recharge schemes.

Following the initial assessment, borehole injection was tested at several locations in widely varying aquifers and a range of injection rates. It was shown that rural water supply schemes could be augmented by small-scale injection systems using suitable aquifers. In other cases, such as Windhoek in Namibia, the highly fractured quartzite aquifer will allow high rate injection, which will make a significant contribution to the sustainability of the water supply.

This paper describes the development of MAR in Southern Africa, outlines the existing operational schemes, and describes the Atlantis scheme as a case study.

2 MAR in Southern Africa

In the more arid parts of the subcontinent, farmers are largely dependent on groundwater and the more enterprising ones considered ways and means to extend their supplies. Constructing dams in riverbeds above boreholes solved this problem. However, the dams easily silted up and, in view of the excessive evaporation, the idea originated that a dam filled with sand, i.e. a 'sand storage dam', could serve as a reservoir from which little or no evaporation would occur. Wipplinger (1953) made an extensive study of the subsurface storage of water in such artificial sand aquifers in Namibia and particularly the construction and efficiency of such systems to serve as water supply sources (see Figure 1). His early work can have an important bearing on the use of artificial recharge as a means to reach sustainability in community water supply.

Figure 1. Early stage of sand storage dam construction, Namibia (Wipplinger, 1953).

In Table 1 the MAR schemes in Southern Africa are listed. These include both full-scale and pilot scale operations and were first summarised by Tredoux & Wright (1996).

South Africa

Projections in the early 70's indicated that Cape Town would require additional water from 'unconventional' resources, (i.e. not from surface water impoundments) before the turn of the century. Many megalitres of high quality purified wastewater freely flowing into False Bay seemed an obvious, economical resource to exploit (Henzen, 1975). International collaboration was sought and the idea was that the two countries, Israel and South Africa, should both run soil-aquifer-treatment (SAT) indirect recycling systems. It was about at this time when Cape Town abandoned the concept of direct reclamation. In South Africa SAT was aimed at full recycling while in Israel the final product was only intended for non-potable reuse. In Israel water abstracted after SAT is not considered potable if it contains more than five per cent recharged wastewater. Such water is only suitable for irrigation (Idelovitch et al., 1984). On the other hand, Bouwer (1996), argues that potable use of treated effluents after SAT and blending with native groundwater may be possible. The main concern relates to the trace organic compounds that may still be present in the water after SAT. In the Cape Flats near Cape Town, a pilot MAR scheme was constructed with infiltration basins for recharging treated domestic wastewater to the Cape Flats sandy aquifer (Tredoux et al., 1980). This was operated successfully and proved the viability of the concept but a full-scale abstraction and recharge scheme has not been constructed.

Table 1. Summary of MAR schemes tested and constructed in Southern Africa.

Country	Scheme name	Aquifer type	(Planned*) Water source(s)	Recharge Capacity	Purpose	Status (Dec. 2002)	Literature Reference
Botswana							
Full scale	None						
Pilot scale	Shashe River, Maun	Alluvium	Okavango or Thamalakane River	2 - 4 Mm^3/a*	Town supply	Test completed	Eastend Consultants (1997)
Namibia							
Full scale	Omdel	Alluvium	Omaruru River floodwater	ca. 3 Mm^3/a*	Potable & industrial	9 years in operation	Zeelie (2002a)
	Khorixas	Fractured gneiss	Spring flow	Unknown	Potable		Zeelie (2002b)
	Various	Sand storage	River floodwater	Relatively small	Stock watering	In operation	Wipplinger (1953)
Pilot scale	Windhoek	Fractured quartzite	Surface water impoundments	5 Mm^3/a (phase I)	Potable & industrial	Full scale planned	Murray & Tredoux (2002b)
South Africa							
Full scale	Atlantis	Sand	Urban stormwater & treated wastewater	2 Mm^3/a	Potable & industrial	20 years in operation	Tredoux et. al. (2002)
	Polo-kwane	Alluvium, feeding gneiss	Treated wastewater & river floodwater	4 Mm^3/a	Potable & industrial	Approx. 10 yrs, but unintentional*	Murray & Tredoux (2002a)
	Karkams	Fractured gneiss	Spring flow	0.02 Mm^3/a*	Town supply	7 years in operation	Murray & Tredoux (2002c)
Pilot scale	Cape Flats	Sand	Treated wastewater	0.3 Mm^3/a	Potable & industrial	Test completed	Tredoux et. al. (1980)
	Calvinia	Breccia pipe	Surface water impoundment	0.1 Mm^3 per cycle	Town supply	Test completed	Cave & Tredoux (2002)

* Notes: 'Planned' water source in case of pilot scheme

- Shashe River, Maun, recharge volume estimates only;
- Omdel recharge volume could range from 0 to 9 Mm^3/a depending on floods;
- Polokwane artificial recharge was unintentional, as the discharge system was not planned to augment aquifer;
- Karkams injection volume is small but important both from quantity and quality viewpoint.

Despite these initiatives, nearly three decades ago, most of the high quality treated wastewater at Cape Town is still being lost to the sea. However, the Atlantis development benefited from these experiences (Tredoux & Tworeck, 1984) and a full-scale MAR scheme was completed in 1980, which is described in par. 3.

At Polokwane in the Limpopo Province, the fractured granitic gneiss aquifer is being recharged indirectly via the alluvium in and alongside the Sand Riverbed. The aquifer is used for town supply to Polokwane. The flow in the river consists of floodwater and treated wastewater. Recharge of the aquifer in this way is unintentional and concern exists that the aquifer will become polluted with organic compounds derived from the wastewater (Murray & Tredoux, 2002a).

At Karkams an ephemeral spring dissipating into the alluvium was intercepted for injection into a production borehole in granitic terrain (Murray & Tredoux, 2002c). This operation only augments the water supply by some 0.02 m3/a (see Figure 2). However, in this very arid environment it constitutes a significant improvement in the reliability of supply. In addition, the low salinity spring water significantly improves the quality of the water in the aquifer.

Figure 2. Filter for ephemeral spring, with injection borehole in background, Karkams (Murray & Tredoux, 2002c).

Calvinia is located near the western edge of the arid Karoo and has recurring water shortages. Pilot scale tests were carried out to investigate the possibilities of utilising a breccia pipe with significant voids as a reservoir for subsurface storage of surplus surface water. In this case, the geochemistry of the minerals contained in the breccia pipe reacted with the injected water and imparted chemicals to the water, which rendered it non-potable (Cavé & Tredoux, 2002).

Botswana

Maun, which is situated at the lower end of the Okavango Delta in Botswana, is dependent on the floodwater from the Okavango River for its water supply. The intermittent floods provide surface water for a limited period each year but also recharge the alluvial aquifers associated with the river system. The annual extent of the floods differs significantly and aquifer recharge is erratic. As a result, Timm (1987) proposed an MAR scheme and carried out pilot scale infiltration runs.

These were only partially successful and a decade later Eastend Consultants (1997) successfully completed further tests. Mathematical modelling, using the pilot scale test results, hinted at the feasibility of a large scale MAR system in the Shashe River.

However, in the meantime other wellfields, mostly more remote, were developed for replacing the depleted ones and the MAR scheme has not yet been constructed.

Namibia

In Namibia the MAR concept has found greater acceptance the past decade or longer. The Omdel MAR scheme was constructed in the Omaruru River Delta, in the Namib Desert, 35 km from the coast. It consists of the Omdel Dam (see Figure 3) with a capacity of 40 Mm3 and a series of infiltration basins constructed in the riverbed (see Figure 4) where the present channel crosses paleo river channels (Zeelie, 2002a). The main impoundment serves as a silt trap and after settling, the water is allowed to flow to the infiltration basins. The aquifer provides water to the coastal towns and a large open pit mine.

Figure 3. Omdel impoundment in the Omaruru River, Namibia (December, 2000).

Figure 4. Infiltration basin in the Omaruru River Delta, Namibia (December, 2000).

Similar to the Karkams injection system, a spring was intercepted at Khorixas in the arid northwestern Namibia and gravitated into two unused production boreholes (Zeelie, 2002b). This has been in operation since the middle of the year 2000.

The Windhoek aquifer was investigated as part of the research into the feasibility of recharging fractured aquifers (Murray & Tredoux, 2002a). A detailed geological, structural and hydrogeological investigation was carried out of the quartizitic aquifer providing water to Windhoek. Subsequently, pilot scale injection tests were carried out using potable water from the water supply system. This water was further treated with activated carbon (see Figure 5) for removing traces of organic compounds. High injection rates were achieved and it was evident that injection was feasible (Murray & Tredoux, 2002b). The concept of water banking makes the injection scheme economically attractive as it reduces the risks associated with the city water supply in periods of drought.

Figure 5. Activated carbon filter, Windhoek (Murray & Tredoux, 2002b).

Based on the results of the pilot scale tests, a full-scale system has been designed and will be implemented in various phases.

3 Case study: Atlantis MAR

At its inception in 1976, the town of Atlantis, located 50 km north of Cape Town, was fully dependent on groundwater. Groundwater supplies are limited and artificial recharge was introduced shortly afterwards for augmenting local groundwater supplies. The recharge system, using urban stormwater runoff and high quality treated domestic wastewater, has been in operation for more than 20 years. The population of Atlantis exceeds 100 000.

Atlantis is located along the semiarid to arid West Coast of South Africa (see Figure 6) and enjoys a Mediterranean climate, with most of the 450 mm mean annual rainfall received from April to September. As a result of the sandy surface over most of the area, natural recharge amounts to 15 or even 30% of the annual rainfall, with the higher recharge occurring in the unvegetated dune area.

The town was planned with fully separated residential and industrial areas. This fact contributed to the success of the artificial recharge operation, as diversion of stormwater and wastewater flows of inferior quality from the industrial area was possible. Since 1999, the scheme was augmented with a limited supply from surface water sources to meet peak demands, but the town is still mainly dependent on the local groundwater.

The coastal aquifer system in the Atlantis area is formed of unconsolidated Cenozoic sediments overlying bedrock of greywacke and phyllitic shale. The total sand cover reaches a thickness of 60 m in the central area, with an average

Figure 6. Location and layout of Atlantis water supply system.

thickness of 25 m. The bedrock also contains groundwater, but the weathered upper zone of the shale forms an impervious clay layer preventing any exchange of groundwater. Groundwater flows westwards to south-westwards and discharges along the coast in areas where the aquifer dips below sea level. The groundwater table has a relatively steep gradient (approximately 1 : 58) towards the coast. The saturated thickness varies considerably, but seldom exceeds 35 m in the thickest regions, where abstraction takes place. Due to topographic constraints, artificial recharge is only practised near the southern Witzand wellfield.

Stormwater was seen as a valuable water source for augmenting freshwater supplies in this semiarid region and prompted the construction of a urban stormwater runoff collection system (Tredoux & Tworeck, 1984). It consists of twelve detention and retention basins and the necessary interconnecting pipelines with peak flow reduction features (Liebenberg & Stander, 1976). It was designed with the flexibility to control water flows of differing salinity and to collect the best quality water for infiltration into the aquifer. Low salinity flows are channelled into two large spreading basins, Basin 7 and Basin 12, for artificial recharge up gradient of the Witzand wellfield. Higher salinity baseflow is diverted to the coastal basins or to the Donkergat River in the south (Figure 6). Discharges during storm events can reach up to 72 000 m^3/d at Atlantis, while summer baseflow, averages 2160 m^3/d. Secondary treated wastewater was also considered to be a reusable water resource at Atlantis. Apart from partial direct reuse for irrigation, the treated domestic component is recharged to the aquifer along with the stormwater, rather than being discharged via a marine outfall.

Stormwater and wastewater infiltration augments the natural recharge of the groundwater in the Witzand unit by 1.5×10^6 to 2.5×10^6 m^3/yr. Treated industrial wastewater, softening plant regenerant brine, and industrial area stormwater, together exceeding 2×10^6 m^3/yr, is discharged into the coastal recharge basins. The basin areas, average thickness of the unsaturated zone, and average infiltration rates are given in Table 2. Basin 7 is generally wet but was dried out and scraped in 1990. Basin 12 often dries out as it only receives peak flows.

Table 2. Recharge facility characteristics (average values).

Facility	Area* (ha)	Unsaturated zone (m)	Infiltration rate (m/day)**
Basin 7	28.3	1.5	0.01
Basin 12	16.8	8.5	0.16
Coastal Basin	12.5	10.5	0.11

* Total basin area when full; Basin 12 mostly dry

** Rate based on total basin area

Managing water quality and, in particular, salinity has been one of the greatest challenges for the Atlantis Water Scheme (Cavé & Tredoux, 2002). High quality, low salinity groundwater (electrical conductivity < 70 mS/m) occurs in the high natural recharge areas around the central Witzand dunes (see Figure 6). Water of marginal quality generally borders the low salinity regions of the aquifer, particularly where the aquifer thins out against the bedrock. Salinity in the Atlantis aquifer is derived from several sources, e.g. wind-blown salt aerosols from the Atlantic Ocean, leaching of shale bedrock outcrops, and those sediments that are of marine origin. The partial recycling of water in the system, whereby treated wastewater from the town is infiltrated back into the aquifer, contributes to the salinity problem. The recent importation of limited quantities of surface water represents an important additional source of low salinity fresh water entering the system. Domestic and industrial wastewater is treated separately in twin wastewater treatment works and the final effluent from only the domestic works used for recharge upgradient of the wellfield. The more saline industrial effluent is discharged into the basins at the coast (see Figure 7), together with the higher salinity stormwater and diluted waste brines from the softening plant. The positive effect of the salinity management can be seen at the Witzand wellfield (see Figure 8).

Figure 7. Coastal recharge basins, Atlantis.

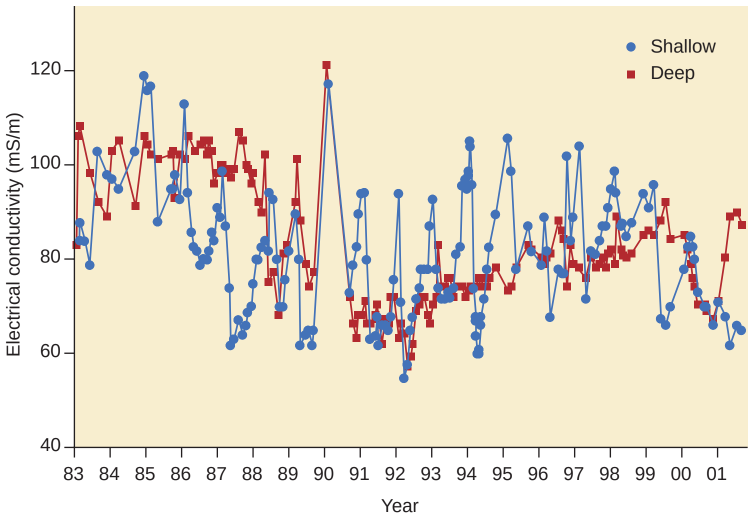


Figure 8. Groundwater quality at the Witzand wellfield.

Protection of the aquifer was fortuitously taken into account when planning the Atlantis development with the result that most of the potentially polluting activities take place in more saline areas with poorer groundwater potential. The Wastewater Treatment Works and the other "noxious" industries are separated from the main Witzand unit by high bedrock, which acts as a groundwater divide.

Production borehole clogging is a problem that occurs all over the world. It is a complex phenomenon caused by a variety of physical, chemical and biological factors, functioning singly or in combination with each other. A decline in the yield of the boreholes in the Atlantis aquifer led to the discovery of extensive clogging problems. The widespread nature of the problem and the presence of iron and sulphate in the groundwater pointed to biological, iron-related clogging rather than physical clogging of individual boreholes. The root cause of the biofouling problem was suspected to be over pumping of the boreholes, which allowed ingress of oxygen into the aquifer.

Artificial groundwater recharge ensured the sustainability of the Atlantis water supply over two decades and will continue to play a key role.

Indirect recycling of stormwater and treated domestic wastewater augments the limited groundwater supplies in a publicly acceptable manner. Water quality management remains the dominant issue regarding water supply at Atlantis. Separation of source water into different fractions allowed recharge of the highest quality water in the areas of importance for the production wellfield.

The Atlantis groundwater scheme provides a cost-effective water supply option when coupled with strict management of the resource. The importation of limited quantities of low salinity surface water has enhanced the viability of the recharge scheme and also allows the utilisation of slightly more saline groundwater.

4 MAR perspective for the region

In southern Africa, and in particular, in the arid and semi-arid areas, the main need is to have a reliable source of water. This is usually of greater importance than having water of high quality.

From a sustainability perspective (and in some cases, a water quality perspective), MAR plays an important role in ensuring the reliability of aquifers that are vulnerable to over-exploitation. Not only is there value in rapidly replenishing aquifers with low natural recharge, but it is also sound management to store water in the subsurface to minimise evaporation and pollution hazards.

In southern Africa both the aridity of the region and the predominance of hard, fractured rock aquifers makes the successful implementation of MAR a scientific and engineering challenge. The successful application of this technique, has however demonstrated the value of integrating surface and groundwater resources.

The range of system sizes varies considerably in the region. In Windhoek, the first phase, out of a three-phase implementation strategy, is due to deliver 5 to 10 Mm^3/a. This compares with Karkams and Khorixas where only tens of thousands of cubic metres of water is injected annually. Although the range of system sizes varies considerably in the region, this technique is valued very highly because of the critical importance for the water supply under arid conditions.

5. Conclusions

The successful application of MAR has been demonstrated in unconsolidated, primary aquifers in Southern Africa. The best example of this is Atlantis, which has been in operation for two decades. Over the past five years, research has been done to assess the feasibility of artificially recharging southern Africa's fractured aquifers. To test this, suitable hard-rock aquifers and test sites, ranging from very small applications to large-scale applications, were identified. The large-scale Windhoek pilot study and the very small scale Karkams application confirmed the wide range of situations where the technique can succeed. This is important for large towns with extensive infrastructure and skilled staff, and for rural communities with minimal infrastructure and human resources.

MAR is currently an important technology in southern Africa, but to date has not been used extensively. There exists vast potential for applying MAR throughout the region where suitable water sources and aquifers exist. Where previously the technology was only applied to sandy aquifers, it has now been successfully demonstrated in complex, fractured rock environments.

Literature

- ***Bouwer, H.***, 1996. Issues in artificial recharge. Wat. Sci. Tech., 33, 381 - 390.
- ***Cavé, L.C. & Tredoux, G.***, 2002. Chemical processes at two artificial recharge sites in South Africa. In: Dillon, P.J. (Ed), 2002. Management of Aquifer Recharge for Sustainability. Swets & Zeitlinger, Lisse, 101 - 106.
- ***Eastend Investments (Pty) Ltd.***, 1997. Maun groundwater development project. Phase I: Exploration and resources assessment. Contract TB 10/3/26/94-95. Report to Department of Water Affairs, Gaborone, Botswana.
- ***Henzen, M.R.***, 1975. The use of sandy aquifers for the storage and reclamation of purified sewage effluents. Paper presented at the International Symp. Recycling of Wastewater for Agricultural and Industrial Uses, Jerusalem, Israel.
- ***Idelovitch, E., Kanarek, A., Michael, M. & Goldman, B.Z.***, 1984. Dan Region Project: Treatment and groundwater recharge of municipal wastewater: Year 1983. TAHAL Water Planning for Israel, Tel Aviv.
- ***Liebenberg & Stander*** 1976. Planning and Masterplan for the Stormwater Network, Outfall and Disposal System. Report GW/EduT/1961 PC. Cape Town: Liebenberg & Stander Consulting Engineers.
- ***Murray, E.C. & Tredoux, G.***, 1998. Artificial recharge, a technology for sustainable water resource development for community water supplies. Water Research Commission Report No 842/1/98, Pretoria, ISBN 1 86845 450 9.
- ***Murray, E.C. & Tredoux, G.***, 2002b. Borehole injection tests in Windhoek's fractured quartzite aquifer. In: Dillon, P.J. (Ed), 2002. Management of Aquifer Recharge for Sustainability. Swets & Zeitlinger, Lisse, 251 - 256.
- ***Murray, E.C. & Tredoux, G.***, 2002c. Karkams borehole injection tests: Results from injection into a low-permeability fractured granitic aquifer. In: Dillon, P J (Ed), 2002. Management of Aquifer Recharge for Sustainability. Swets & Zeitlinger, Lisse, 301 - 304.
- ***Murray, E.C. & Tredoux, G.***, 2000. Testing borehole injection for artificially recharging secondary aquifers in Southern Africa. In: Groundwater: Past achievements and future challenges, Sililo et al. (eds) 2000, Balkema, Rotterdam, ISBN 905809 159 7.
- ***Murray, E.C. & Tredoux, G.***, 2002a. Pilot artificial recharge schemes: testing sustainable water resource development in fractured aquifers. Report to the Water Research Commission, WRC Report No 967/1/02, Pretoria. ISBN 1 86845 883 0.
- ***Timm, J.***, 1987. Shashe River well field, Maun: Progress in overcoming the present water supply shortages. DWA Report JT12/GWD8-87, Gaborone.
- ***Tredoux G., Ross W.R. & Gerber A.***, 1980. The potential of the Cape Flats aquifer for the storage and abstraction of reclaimed effluent (South Africa). Z. dt. geol. Ges., 131, 23 - 43.
- ***Tredoux, G., & Tworeck, W.***, 1984. Artificial recharge of an unconfined aquifer at Atlantis. Paper presented at the International Conference on Groundwater Technology, Johannesburg, South Africa, 14 - 17 November.
- ***Tredoux, G., & Wright, A.H.***, 1996. Artificial groundwater recharge in Southern Africa. Paper presented at Workshop on aquifer recharge held at Warmbaths. Water Research Commission, Pretoria, September 1996.
- ***Tredoux, G., Cavé, L.C., & Bishop, R.***, 2002. Long-term stormwater and wastewater infiltration into a sandy aquifer, South Africa. In: Dillon, P J (Ed), 2002. Management of Aquifer Recharge for Sustainability. Swets & Zeitlinger, Lisse, 35 - 40.
- ***Tredoux, G., King, P.B., & Cavé, L.C.***, 1999. Managing urban wastewater for maximising water resource utilization, Wat. Sci. Technology, 39, 353 – 356.
- ***Wipplinger, O.***, 1953. The storage of water in sand. Ph. D. dissertation, Faculty of Engineering, Univ. of Stellenbosch, 215 p.
- ***Zeelie, S.***, 2002a. OMDEL dam and recharge ponds to enhance recharge in the Namib Desert. In: Dillon, P.J. (Ed), 2002. Management of Aquifer Recharge for Sustainability. Swets & Zeitlinger, Lisse, 387 - 392.
- ***Zeelie, S.***, 2002b. Written communication, November 2002

9 Recharge enhancement and subsurface storage

Summary report of the 18 - 19 December seminar, submitted by the NNC-IAH to the Dialogue on Water and Climate (DWC)

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Abstract

Providing sufficient storage capacity under growing water demands and increasing climate variability is a main concern for water managers in the coming decades. It is expected that 2000 - 3000 km^3 of additional storage capacity will be needed by 2025 especially in (semi)-arid regions where changes in climate variability will have most impact on rainfall and drought. Storage in surface water reservoirs behind dams will have to be supplemented with a substantial increase of subsurface storage in aquifers. Recharge enhancement and subsurface storage is a known technology and already successfully applied in many countries for many years at different scales. It represents a flexible and cost effective means to increase storage capacity both at village level and in modern water management schemes. Completing the current global inventory of subsurface storage schemes and creating a platform for exchange of experiences and good practices are first steps for a wider application. Data on climate variability can contribute to planning, design and operation of subsurface storage schemes.

Keywords: groundwater, storage, recharge, water conservation, dams, reservoirs

1 Introduction

Provision of sufficient storage capacity under growing water demands and increasing climate variability is one the main concerns for water managers in the coming decades. Accurate estimates do not exist, but it is expected that the availability of sufficient storage will be come a key issue in securing water supply to the growing urban and rural population under changes in climate variability.

Storage of substantial amounts of water can either be above ground, in reservoirs behind dams or underground in aquifers (subsurface storage). Surface water storage behind large (and small) dams is widely applied and represents the major part of the installed global storage capacity. However the recognition of the environmental and social impacts, the growing concerns about dam safety issues and increased sedimentation has clearly demonstrated the limitations of large dams. Meanwhile there has not been a significant increase in the controlled use of aquifers for subsurface storage. Yet, a debate on the limitation of large dams has less value if there are no alternatives to maintain even minimum supply levels to millions of people both in rural and urban areas.

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2 Objective(s)

The objective of this study is to identify the current and future storage needs in water management under changes in water demand and climate variability and to assess the potential role of recharge enhancement and subsurface storage as a complimentary provider to surface water storage.

3 Approach

The study will identify the current status of recharge ehancement and subsurface storage in the world and assess its current and potential importance as a means to cope with increasing storage requirements. Activities included:

1. Consultations with groundwater experts during the ISAR 4 conference (International Seminar on Artificial Recharge) in Adelaide (Australia) and a two day workshop on Evaluation of Recharge Enhancement projects in Arid and Semi-arid Countries (September 2002).
2. The initiation of global inventory of subsurface storage schemes in association with the IAH Commission on Management of Aquifer Recharge (IAH-MAR).
3. Preparation of a status report on current storage practices and potential of recharge enhancement and subsurface storage and its contribution to coping strategies for climate change (October 2002 - January 2003).
4. A two-day international seminar on subsurface storage in the Netherlands (18 - 19 December 2002) organized by the NNC-IAH with support of UNESCO and the Worldbank.
5. Finalizing the recommendations, submission to the ISC-DWC and printing of the proceedings of the workshop (January - February 2003).

4 Results

Availability of storage capacity is a crucial link in the water supply chain. To supply the current global water demand of 4000 km^3/yr, a storage capacity of at least 6000 km^3 is used to assure water availability at the time when needed:

– surface water storage behind large and small dams represents an aggregate capacity of at least 6000 km^3 (source IWMI) and an estimated effective capacity of approximately 3000 km^3;
– natural groundwater storage (representing the groundwater pumped during dry periods when the groundwater table drops under continuing groundwater abstraction and is replenished through natural recharge during the subsequent period with excess rain.), represents also an estimated capacity of 3000 km^3 (estimated by NNC-IAH).

IWMI and others estimate that replacement storage will be needed in the coming decades to compensate for sedimentation of existing reservoirs (60 km^3/yr) and for the current over draft of groundwater (200 km^3). In addition there will be an urgent need for additional storage to respond to the increasing water demands to feed the growing global population under changes in climate variability (droughts). Our estimate is that an additional 2000 - 3000 km^3 of life storage capacity will needed by 2025, especially in semi-arid and arid regions where changes in climate variability lead to longer dry periods. With a storage:release ratio of 1 : 3, this volume is equivalent to is equivalent to at least 15 - 20 High Aswan Dams! It is unlikely that large dams and reservoirs alone can provide all future storage needs and it is therefore urgently needed to explore the additional contribution that can be provided by subsurface storage.

Subsurface storage (or groundwater storage) represents the volume of water available for pumping during dry periods and can be replenished during the subsequent wet period through enhancement of the (natural or artificial) recharge. subsurface storage has some comparative advantages compared to surface water storage (see table)

Characteristics of groundwater storage, small dam storage and large dam reservoirs.

	Groundwater storage	Small dams & surface storage	Large dam & reservoirs
Advantages	Little evaporation Widely distributed Operational efficiency Available on demand Water quality	Ease of operation Response to rainfall Multiple use Groundwater recharge	Large, reliable yield Carryover capacity Low cost per m^3 water stored Multi purpose (power & flood control) Groundwater recharge
Limitations	Slow recharge rate Groundwater contamination Cost of extraction Recoverable fraction	High evaporation losses Relatively high unit cost Absence of over-year storage	Complexity of operation Siting High initial investment cost Time needed to plan & construct
Key issues	Declining water levels Rising water levels Management access & use Groundwater salinization Groundwater pollution	Sedimentation Adequate design Dam safety Environmental impacts	Social impacts Environmental impacts Sedimentation Dam safety

Source: IWMI Research Report no.39: Water Scarcity and the Role of Storage in Development

Recharge enhancement through management of aquifer recharge (MAR) and subsurface storage (SSS) is a known technology and already successfully applied in a number of countries for many years at different scales and through a variety of methods. There is wide variety of the scale and scope of MAR-SSS schemes, ranging from up-catchment community based systems to sophisticated engineering schemes (see table).

Proposed classification of MAR-SSS systems.

MAR-SSS technique	Names used	Country examples
Village level gravity injection	Dug wells, recharge shafts, village tanks trenches, gravity injection wells	India, Thailand, China
In-Channel structures	Gabions, percolation tanks (India), subsurface dams, sand dams, recharge dams	India, Oman, Kenya, Egypt, Namibia
Off- channel infiltration ponds	Large basins sometimes supplemented with injection devices	Netherlands, Egypt, Taiwan
Pressure injection	Injection wells and injection-recovery wells (ASR wells)	USA, Australia
Induced bank infiltration	Sometimes supplemented with injection devices impacts	Germany, Hungary

1 Rock Type: alluvial sand stone, hard rock or lime stone

2 Water source: stream water, rainwater or treated waste water

3 Purpose: water supply, quality improvement, seawater intrusion control, strategic reserves

An ongoing global inventory of MAR-SSS schemes by the IAH-MAR Commission shows the growing interest in development of MAR-SSS in many countries and the variety of technologies that are tested and applied with different water sources, under different climatic and geological conditions and for different purposes. The result of the inventory will verify our estimation of the present capacity (3000 km^3) and provide information on the future potential. A 20% increase represents 600 km^3/year of effective storage capacity and would substantially contribute to future storage needs.

5 Discussion

Management of aquifer recharge and subsurface storage is widely applied and has a great potential but is still hardly recognised at the political level and often also at the local level. Governments and water management authorities show little interest in aquifer management while large (human resources and financial) investments are made for the management of dams and reservoirs. Champions are needed in the political arena to promote management of aquifers and the application of MAR-SSS schemes.

Promotion of MAR-SSS and exchange of good practices and of lessons learned is a first step towards a wider application. Pilot projects, publication of research activities and exchange visits are amongst the proposed actions.

There is a need to assess the financial-economic feasibility of MAR-SSS schemes at different scales in order to promote its importance and to raise investment funds for a wider application.

Water right systems in some countries may pose constraints for the application of subsurface storage schemes for public water supply (e.g. when groundwater rights are given to the owner of the overlaying land). Water rights may have to be reviewed and consolidated in updated water laws and regulatory provisions

Construction of MAR-SSS schemes in water scarce regions is a always complementary to demand management measures and may never be considered a substitute for efforts to improve water conservation and increase water use efficiency.

Mobilising the community has proven to be a successful element for the sustainability of the small-scale MAR-SSS systems and does recognise the important role of women in water management in many rural communities.

MAR-SSS schemes may affect downstream users and downstream functions of the water (social, ecological, economic). These regional impacts (based on a regional vision) of MAR-SSS schemes should be taken into account in the planning and design phase.

MAR-SSS schemes will be more successful if planned and designed in relation to surface water and land use and based on the comparative advantages of groundwater and surface water (integrated planning). Example: construction of dams for surface storage and groundwater recharge enhancement.

Water quality ameliorates during storage because of the healing capacity of sediments. Quality improvement together with the benefits of subsurface storage may lead to large cost savings in wastewater treatment and re-use and recycling of urban runoff water or irrigation return flow.

6 Conclusions

MAR-SSS is a flexible and cost effective means to cope with the impacts of (the irregular) changes climate variability, leading to changes in rainfall patterns and an increase in the frequency and length of drought periods in many regions.

MAR-SSS schemes on village level are a cheap and appropriate means to enhance community-based solutions for seasonal water shortage. High tech engineering MAR-SSS schemes are a important element in densely populated and industrialised (coastal) regions where environmental concerns ask for sophisticated solutions.

Key recommendations for further development of MAR-SSS is:
- Complete the MAR-SSS inventory and disseminate it through the IAH-MAR website (www.IAH.ORG) and use it to develop a system of permanent exchange of good practices between countries with comparable conditions and compatible interests (including study tours and exchange visits).
- Prepare a global overview of regions where changes in climate variability will result in longer periods of drought, prepare estimates of additional storage capacities that can be created through MAR-SSS and investigate how climate models can be used to plan and operate MAR-SSS schemes.

Acknowledgements

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References

- ***IWMI*** Research Report no.39: Water Scarcity and the Role of Storage in Development and some other papers of IWMI available on the internet
- ***IAH/UNESCO***, 2003, Recharge Enhancement and Sub-Surface Water Storage Proceedings of the IAH/UNESCO seminar at Wageningen, 18 December 2002 (under preparation)

10 Conclusions and recommendations of the workshop
Wageningen-Amsterdam; 18 - 19 December 2002

Conclusions

1. In order to assure the water supply to the growing population under changes in climate variability, growing water demands and increase erosion and catchment degradation, the availability of storage capacity is increasingly becoming a crucial element of the water chain.

2. It is estimated that a multiple of the present storage capacity will be needed in the coming decade to provide water during dry periods, especially in semi-arid and arid regions where changes in climate variability lead to longer dry periods.

3. Surface water storage behind large and small dams represents the major part of the installed global storage capacity. However, surface water storage is largely complemented by natural groundwater storage, when during dry periods groundwater tables drop under continuing groundwater abstraction, which can be replenished through natural recharge during the subsequent period with excess rain.

4. Natural recharge and groundwater storage can be enhanced by management of aquifer recharge and optimising the storage capacity of the aquifers. As such groundwater storage provides an important additional storage capacity. Estimates show that 1000 km^3 of additional subsurface storage could be created.

5. For many years management of aquifer recharge and subsurface storage (MAR-SS) is a known technology and applied in a variety of methods at different scales in a number of countries.

6. An ongoing global inventory of MAR-SS schemes shows the growing interest in development of MAR-SS in many countries and the variety of technologies that are tested and applied with different water sources, under different climatic and geological conditions and for different purposes.

Recommendations

1. Complete the MAR-SS inventory and disseminate it through the IAH-MAR website.

2. Use the inventory to develop a system of permanent exchange of good practices between countries with comparable conditions and compatible interest.

3. Prepare a global overview of regions where changes in climate variability will result in longer period of drought and prepare estimates of additional storage capacities that can be created through MAR-SS and investigate how climate models can be used to plan and operate MAR-SS schemes.

IAH: Stephen Foster, Albert Tuinhof: Theo Olsthoorn, Jan Piet Heederik, Jacobus de Vries

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Solutions in Groundwater

The Acacia Institute

The Acacia Institute is a not-for-profit and independent knowledge centre on groundwater, affiliated to Faculty of Earth and Life Sciences of the Vrije Universiteit Amsterdam. Its mission is:

- to promote the often neglected role of groundwater in land and water management,
- to enhance exchange of groundwater knowledge for all stakeholders and
- to provide support in policy formulation and program management.

Acacia focal points

Combing the expected changes in climate and increasing global water demands with the "state of the art" in groundwater knowledge and science, Acacia foresees an growing interest in:

- development of onshore and offshore brackish groundwater resources for water supply and biosaline agriculture,
- subsurface storage of water for water supply, water quality control and restoration of natural ecosystems,
- utilization of the aquifer capacity for natural attenuation of contaminated water.

Acacia people

Acacia's founders and managing directors are:

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Acacia Institute

vrije Universiteit amsterdam


Place it behind
a dam, pump it out
or let it flow

igrac

facilitates and promotes world-wide exchange of groundwater knowledge...

...to improve assessment, development and management of groundwater resources

The International Groundwater Resources Assessment Centre (IGRAC) – an initiative of UNESCO and WMO - is founded in spring this year. The Centre aims to promote the availability of sufficient and reliable groundwater data and to facilitate the exchange of groundwater knowledge for the benefit of all those who have a stake in groundwater. IGRAC has defined three main fields of activity:

- development of a Global Groundwater Information System (GGIS);
- development and promotion of guidelines and protocols for the assessment of groundwater resources,
- participation in global and regional projects in need of groundwater-related inputs.

The Centre is hosted at the Netherlands Institute of Applied Geoscience TNO and is financially supported (for the initial period) by the Dutch interministerial bureau 'Partners for Water'. IGRAC is a non-commercial centre and it welcomes any initiative for cooperation that may assist in achieving its goals.

Contact:

IGRAC

International Groundwater Resources Assessment Centre

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The Netherlands Water Partnership (NWP) is an independent non-profit organization set up by the Dutch private and public sectors. Its mission is to promote the Dutch water sector, to improve communication and synergy between parties in the Netherlands and overseas, to encourage Dutch contributions to international water policy development and to represent Dutch views and interests to the water community.

NWP members represent central, provincial and municipal governments, knowledge and research institutes, water boards and NGOs, water supply companies, consultancy firms, contractors, manufacturers and financial institutions. NWP's innovative and proactive approach is reflected in its activities:

Water Information Network (WIN)
This online database (www.nwp.nl) matches supply and demand of water expertise and provides a meeting place for people working on collaborative projects. Overseas visitors can search for Dutch experts~~,~~ or submit requests for assistance or cooperation, which are subsequently distributed to the most relevant Dutch organizations or contacts.

Product-market combinations (PMCs)
NWP has launched four product-market combinations (PMCs), in which Dutch expertise and knowledge on a specific theme are concentrated. E.g. the Groundwater PMC represents extensive (international) Dutch expertise on assessing and managing groundwater resources. Groundwater management has for years been a priority in the Netherlands. The Dutch water sector has built up a considerable expertise in assessing and managing the sustainable development of groundwater resources. This expertise has for years been exported abroad and enriched by the experiences gained, and has been brought together in the PMC Groundwater.

PMC Groundwater in Johannesburg 2002

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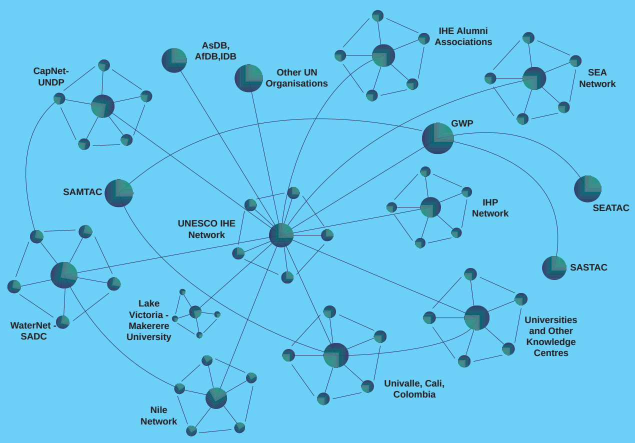
Postgraduate education, training and capacity building in water, environment and infrastructure

In March 2003, IHE transformed into the UNESCO-IHE Institute for Water Education.
By becoming part of the intergovernmental structure of the UN, UNESCO-IHE will achieve a more visible impact in developing countries and countries in transition.

UNESCO-IHE:

- strengthens and mobilises the global educational and knowledge base for integrated water resources management.
- contributes to the education and training of capable professionals and build the capacity of knowledge centres and other organisations in the fields of water, environment and infrastructure.
- responds to the needs of the water education sector and provides a platform where consumers and providers meet and match.
- contributes through capacity building in the water sector by means of education, training and research, addressing the themes water security, environmental integrity, urbanisation, integration and information and communication.



To ensure complementarity and impacts in water and environment sectors world-wide, UNESCO-IHE is open to forming new alliances and integrating with other regional and global initiatives, especially where critical gaps exists and benefits are clear.

The UNESCO-IHE network is strengthened by over 12,000 Alumni active in the water, environment and infrastructure sectors since 1957.

New Masters Programmes

Coastal Engineering and Port Development
Environmental Planning and Management
Environmental Science and Technology
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Sanitary Engineering
Surface Water Hydrology
Water Resources Management
Water Services Management
Water Supply Engineering
Water Quality Management

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