Strategies

for Managed Aquifer Recharge (MAR) in semi-arid areas

edited by Ian Gale

Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas

Acknoweldgements

The UNESCO IHP Secretariat wishes to express its profound gratitude to Mr Ian Gale, Principal Hydrogeologist of the British Geological Survey and to Mr Peter Dillon Principal Hydrogeologist of CSIRO Land and Water (Australia) for the preparation of this booklet. The booklet is a contribution to the UN MDG and is an example of the achievements reached by scientists from different countries.

Alice Aureli
UNESCO's International Hydrological Programme (IHP)

Published in 2005 by the United Nations Educational, Scientific and Cultural Organization (UNESCO), 7 Place de Fontenoy, 75352 Paris 07 SP.
Layout and typesetting by Eric Lodde
Printed by Graph 2000 IHP/2005/GW/MAR

Contents

Foreword

Peter Dillon *Chair, IAH-MAR Commission*

Many international, national and local organisations see great potential for recharge enhancement to increase the security and quality of water supplies in water-scarce areas. But if such projects are to succeed, they need to be well planned, designed and operated, and should be an integral part of catchment/basin-wide water management strategies.

A meeting of representative organisations at UNESCO in Paris on 25-26 April 2002, agreed to produce coherent plans and activities and to speak with one voice. This document forms part of this initiative and we hope that this will spark other individuals and organisations to contribute to future joint initiatives to make all new recharge enhancement projects sustainable.

This document has been compiled by the IAH Commission on Managed Aquifer Recharge (MAR) with the support of UNESCO International Hydrology Programme (IHP) and the British Department for International Development (DFID). Ian Gale (British Geological Survey) and Peter Dillon (CSIRO, Australia) have drawn together contributions from a wide range of sources and contributors, whose input is gratefully acknowledged.

The purpose of this document is to draw together experience of application of MAR in semi-arid regions in order to provide guidance and examples of good practice throughout the world. It provides insight into implementing and managing aquifer recharge as part of wider water management strategies and, together with other UNESCO-IAH activities, will help to promote networking, information sharing and improved understanding and implementation of sustainable MAR schemes.

Actions achieved and planned include:

- Information leaflet – September 2002.
- Briefing note for Kyoto 2003.
- Strategies for Managed Aquifer Recharge - this document.
- Workshop on evaluation of recharge enhancement in Arid and Semi-arid Areas – Adelaide, 20-22 September 2002.
- A report on enhancing recharge with reclaimed water - WHO, 2003.
- Conference report on "Management of Aquifer Recharge and Subsurface Storage" IAH/NHV/UNESCO, 2003.
- A symposium on managing risks associated with recharge of reclaimed water – IAHS/WHO/IAH, Sapporo 7-8 July 2003.
- Producing further publications; running regional training programmes. Ongoing
- Facilitating data collection; monitoring and evaluation of projects. Ongoing
- Facilitating networking and dissemination of information (www.iah.org/recharge).
- Contributing to Regional Workshops on "Management of Aquifer Recharge and Water Harvesting"
  – UNESCO-IHP/ISESCO. Yazd, Iran. 27 Nov. – 1 Dec. 2004.
  – UNESCO-IHP/PCRWR, Lahore, Pakistan. 25 April - 2 May 2005.
  – UNESCO/IAH, Hanoi, Vietnam. 15 - 17 Dec 2004.
- Workshop on implementation of MAR in developing countries. Berlin, 11 June 2005.
- UNESCO-GEF/STAP Workshop on MAR, UNESCO New Delhi Office, September 2005.

Objectives of MAR

Managed Aquifer Recharge (MAR) has the potential to be a major contributor to the UN Millennium Development Goals for water supply, especially for village supplies in semi-arid and arid areas.

The benefits of using groundwater have been clearly demonstrated; aquifers providing a store of water, which, if utilised and managed effectively, can play a vital role in:

- Poverty reduction/livelihood stability
- Risk reduction; both economic and health
- Increased agricultural yields resulting from reliable irrigation
- Increased economic returns
- Distributive equity (higher water levels mean more access for everyone)
- Reduced vulnerability (to drought, variations in precipitation)

Managed Aquifer Recharge (MAR) and rainwater harvesting contribute to the maintenance of the above benefits, particularly if practiced as part of a wider approach to water resource management that addresses demand and quality dimensions as well as supply aspects.

MAR often provides the cheapest form of new safe water supply for towns and small communities. Uptake has been limited by lack of understanding of hydrogeology and/or knowledge of MAR. With training and demonstration projects, MAR has potential to be a major contributor to the UN Millennium Goal for Water Supply, especially for village supplies in semi-arid and arid areas.

MAR describes intentional storage and treatment of water in aquifers. The term 'artificial recharge' has also been used to describe this, but adverse connotations of 'artificial', in a society where community participation in water resources management is becoming more prevalent, suggested that it was time for a new name. Managed recharge is intentional as opposed to the effects of land clearing, irrigation, and installing water mains where recharge increases are incidental. MAR has also been called enhanced recharge, water banking and sustainable underground storage.

MAR is part of the groundwater manager's tools, which may be useful for re-pressurising aquifers subject to declining yields, saline intrusion or land subsidence. On its own it is not a cure for over-exploited aquifers, and could merely enhance rates of abstraction. However it may play an important role as part of a package of measures to control abstraction and restore the groundwater balance. MAR can also play a central role in water harvesting and reuse. Many cities drain storm water to aquifers via infiltration basins, sumps or wells and subsequently reuse this water in drinking or irrigation supplies.

Well-informed communities, town planners, developers, water utilities and regulators are better able to scope out innovative solutions that reduce the water footprint of urban areas and create more sustainable and attractive cities. Hydrogeologists are central to creating an awareness of the role that MAR can play within their geological setting, and to guiding communities towards best solutions.

Managed Aquifer Recharge and Rainwater Harvesting have been practiced in arid and semi-arid regions of the world for centuries using a wide range of techniques. Methods used and the effectiveness of these interventions is controlled, not only by physical, but also social and economic drivers. Knowledge gained through experience, including unsuccessful schemes, is often poorly disseminated and the effectiveness of schemes is often poorly assessed. This document attempts to draw together current knowledge and provide some examples of good-practice from around the world.

The following check-list draws together issues that should be considered when assessing the applicability of MAR as part of a water management strategy or assessing the effectiveness of existing schemes. Further information and guidance is given in the text, in the examples of good-practice given at the end of this document and in the references, more of which can be found in the searchable database on **www.iah.org/recharge** and **www.unesco.org/water/**

WHAT ARE THE OBJECTIVES AND BENEFITS OF MAR?

- To store water in aquifers for future use
- To smooth out supply/demand fluctuations
- As part of an integrated water management strategy
- To stabilize or raise groundwater levels where over-exploited
- Applicable where no suitable surface storage site available
- Reduce loss through evaporation and runoff
- Impede storm runoff and soil erosion
- Improve water quality and smooth fluctuations
- Maintain environmental flows in streams/rivers
- Manage saline intrusion or land subsidence
- Disposal/reuse of waste/storm water

WHAT IS THE SOURCE OF WATER?

- Perennial stream/river/canal
- Intermittent stream/wadi/flood flow
- Storage dam
- Urban storm-water
- Treated potable water
- Rooftop rainwater harvesting
- Waste/reclaimed water

HOW CAN A SITE BE ASSESSED?

- Develop a hydrogeological conceptual model (understanding)
- Understant the hydrology (inc. meteorology)
- Estimate space in aquifer to store additional water
- Quantify the components of the water balance
- Assess the quality of groundwater and source water
- Use numerical models to assess scheme
- Assess the impacts downstream of the structure

HOW SHOULD AQUIFERS BE RECHARGED?

- Spreading, Infiltration ponds/inter-dune ponds
- Stream-bed modification
- Open wells, shafts and trenches
- Borehole recharge
- Induced bank filtration
- Soakaways from roof-top catchments

WHAT ARE THE IMPLICATIONS FOR WATER QUALITY?

- Removal of suspended solids, pathogens, heavy metals, organics, nitrates etc from source water.
- Dilution of poor quality groundwater
- Possible contamination of high quality groundwater
- Increase in solutes through mixing and dissolution
- Adverse geochemical reactions (As, F, Fe, Mn)

WHICH INSTITUTIONAL AND MANAGEMENT ASPECTS NEED TO BE CONSIDERED?

- Water rights
- Land ownership
- Legal and regulatory issues
- Who pays and who benefits?
- Who manages?
  - Community/NGO?
  - Local/central government/govt. owned company?
  - Municipality/company? - Private/household/private sector agency?
- Integrated management (users/NGO's/Govt.)
- Conjunctive use
- Demand management

HOW CAN THE BENEFITS BE ASSESSED?

- Stabilised/rising piezometric levels
- Increased base (environmental) flow in rivers
- Saline intrusion abatement
- Abatement of land subsidence
- Sustainable groundwater source
- Sustainable irrigated area
- Stabilised soil erosion
- Positive cost/benefit analysis
- Improved livelihoods

COMMON PROBLEMS THAT CAN BE ADDRESSED

- Clogging management
- Misconception of geology/hydrology
- Poor design of infiltration structure/borehole
- Stability of structure/borehole under operating conditions
- Operation/management of scheme
- Poor quality groundwater (diffusive mixing)
- Protection of groundwater quality
- Loss of infiltrated/injected water
- Transition from trial to operational scale
- Policy, societal and religious acceptability
- Availability and dissemination of information/knowledge
- Availability of skills and human capacity

Managed Aquifer Recharge is carried out globally for all kinds of reasons and, in its simplest form involves constraining surface runoff and encouraging infiltration to aquifers through the construction of earthen field bunds. A large percentage of schemes are developed to store water for future use, for drinking water supplies and agriculture. Other reasons to manage aquifer recharge include the control of saltwater ingress, the augmentation of low river flows, reduction of runoff and soil erosion, absorption of floodwaters to reduce their destructive capacity and the control of subsidence.

Managed aquifer recharge not only provides an effective means of storing water and enabling better management of available resources, but it can also impact on the water quality, usually in a beneficial manner. Changes in quality of both the source water and groundwater result from the physical removal of particulate matter, microbiological removal of pathogens and organic material, dilution or displacement of poor quality groundwater and geochemical interactions with the native groundwater and the aquifer material.

Managed Aquifer Recharge should be regarded as one method to manage water resources in conjunction with a wide range of others, including surface storage, exploitation of groundwater, demand management, water reuse etc.

MANAGED AQUIFER RECHARGE IN VILLAGE LEVEL SCHEMES 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.

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 km^2. Out of total annual precipitation of 4000 x 10^9 m^3 in India, about 1240 x 10^9 m^3 is annually lost as surface runoff. It has been estimated that 870 x 10^9 m^3 of water is still available for recharge and it is feasible to have subsurface storages of 200 x 10^9 m^3. As part of this total feasibility, India plans to have sub-surface storage of 36 x 10^9 m^3 by constructing about 230,000 small and simple recharge structures such as percolation tanks, check dams, sub-surface dykes, etc.

REFERENCE: Chadha, D K. 2003. From Chapter 3 of "Management of Aquifer Recharge and Subsurface Storage." NCC-IAH Publication. No. 4.

Water quality issues and sources of recharge water

The quality of the groundwater, both natural baseline and that altered by Man's activities, and the interactions with the recharged water need to be understood and managed. A prerequisite for managed aquifer recharge of groundwater is the availability of a source of water of suitable quality, in sufficient quantity. Several sources of water can be considered for use as recharge water, namely surface water, runoff water, treated effluent, or potable supply water.

The natural quality of groundwater will vary from one rock type to another, and also within aquifers along groundwater flow paths. Groundwater, where unaffected by anthropogenic impacts, is usually regarded as having excellent quality from the chemical, turbidity and microbiological perspectives. However, groundwater can contain naturally occurring concentrations of iron, manganese, arsenic, fluoride, salinity, boron etc, which render them unacceptable for potable or other uses. The high quality aspects of groundwater result from the natural filtering and microbiological 'treatment' afforded to rainwater and river water as it percolates through the soil zone into the aquifer. Here it is protected, to a greater or lesser extent, from anthropogenic pollution by the overlying strata.

The natural quality of groundwater can be altered as a result of a wide range of anthropogenic activities; the most significant being groundwater abstraction, recharge enhancement, irrigation, land use changes, agriculture and forestry, urbanisation, mining and liquid and solid waste disposal. The biggest threat to groundwater is salinisation through saline intrusion in coastal regions or from deep aquifers, deep percolation of irrigation waters and wastewater returns to aquifers. When considering the impact of recharge in a particular hydrogeological environment it is therefore important to understand the natural quality of the groundwater, the impacts of man's activities and the processes controlling the resultant quality. From this basis the likely impacts of recharge on both the *in situ* groundwater and the water recharged can be predicted and monitored to avoid unacceptable impacts.

In general, where unconfined aquifers have been over-exploited the declines in water levels are eventually accompanied by deterioration of water quality.

Recharge with surplus runoff through surface infiltration structures will usually provide high quality water that will not only replenish resources but also improve quality through dilution or it can be used to provide a hydraulic barrier to lateral saline intrusion (e.g. the coastal sand dune recharge schemes in The Netherlands).

Where treated drinking water or storm water is injected into confined aquifers containing brackish groundwater through recharge wells the quality of the recovered water can deteriorate through mixing and dissolution of minerals, but can also improve through nutrient removal and attenuation of some organic compounds.

In summary, in order to assess the effectiveness of managed aquifer recharge from a water quality view point it is important to have an understanding of the baseline water quality, the impacts of anthropogenic activities and the geochemical processes involved. A reasonable conceptual model can be developed from a groundwater quality sampling programme and a knowledge of the hydrogeology and anthropogenic activities in the area. The likely impacts of appropriate recharge schemes can then be predicted and tested through monitoring.

SURFACE WATER (EXAMPLES B, H, I AND J)*

Surface water can be a significant source of recharge water depending on the climatic situation. Under humid conditions moderate variability in river flows can be expected, but perennial rivers are predominant. Under arid or semi-arid conditions ephemeral rivers prevail. Water from perennial rivers can be diverted to nearby recharge facilities or canalized to more distant facilities. Induced bank filtration directly from rivers is an option commonly employed, although water quality improvement rather than storage is usually the driving factor.

River water can carry considerable quantities of silt in suspension, the amount depending on land cover and the turbulence and 'energy' of the river. Lowland, slow moving rivers generally carry a few tens of g/m^3 whereas mountain streams may carry a few hundreds of g/m^3 and flash flows can increase the suspended load several fold. This suspended load can result in clogging if river water is used directly in recharge facilities. Settling ponds are therefore used before water enters infiltration ponds.

In lakes, water is not flowing significantly and is generally clear with little or no suspended material. In the absence of pollution by waste discharges or agricultural runoff, and with little algal growth, lake water may be used for spreading directly without any pre-treatment (Huisman and Olsthoorn, 1983). Water from polluted rivers or lakes, in particular those with industrial-waste discharges, should go through pre-treatment processes prior to recharge. In some situations infiltration basins can be used to improve the quality of water through physical and biochemical processes as the groundwater is recharged.

STORM-WATER RUNOFF (EXAMPLES A, C, D AND G)

Urban areas generate significant quantities of storm-water runoff. The runoff is highly variable in quantity with peak discharges occurring after heavy rainfalls. In order to obtain a more consistent supply, infiltration and storm-water retention ponds, grassed areas, porous pavements and wetlands are recommended for watershed areas (Murray and Tredoux, 1998).

*See last chapter of this document.

In rural areas, intense rainfall can generate surface runoff from agricultural fields as well as uncultivated land. In some areas (e.g. Saurashtra, India) this runoff is channeled into large diameter hand-dug wells to recharge the aquifer directly. Holding bunds are sometimes constructed to reduce the suspended sediment load, but not the dissolved contaminant load. For this reason direct recharge to open wells is to be discouraged in preference to infiltration through a soil or sand layer which can be managed to remove some of the dissolved constituents, such as nitrogen species, and pathogens through filtration and chemical and microbiological processes.

Storm-water runoff is usually highly variable in quality. The contamination load may include atmospheric deposition on watershed surfaces, road surface accumulation, construction activity, industrial runoff, animal wastes, decaying vegetation, chemicals applied to lawns and gardens, septic tank seepage and litter. The highest contamination load can be observed in the “first flush”, which should be diverted to waste to improve quality. The best quality runoff water in urban areas is from rooftops and increasingly initiatives (e.g. government buildings in India) are being made to direct this water immediately to groundwater recharge through infiltration galleries, wells and boreholes. This not only replenishes urban aquifers that are often over-exploited, but also introduces good quality water into often-polluted groundwater.

The contaminant load in rural runoff from agricultural land can include residual pesticides and fertilisers as well as faecal matter from livestock, human and other sources. When this runoff is recharged directly into the aquifer, the beneficial effects of infiltration through a soil zone are lost and the risk of contamination of the aquifer increases and may need to be offset by other forms of treatment, such as slow sand filtration.

RECLAIMED WATER (EXAMPLE E)

Reclaimed water as a source is of predictable volume with a fairly uniform rate of flow over time and of constant, but inferior quality (Murray and Tredoux, 1998). Wastewater requires significant treatment before being considered to be of acceptable quality for aquifer recharge and to minimise the extent of any degradation of groundwater quality. The compounds of concern depend on the wastewater source, i.e. industrial or domestic wastewater. Wastewater as a source offers a significant potential for all non-potable uses. However, with proper pre- and post-treatment or dilution with native groundwater, potable use also can be a viable option (Bouwer, 1996).

The principle constraints on the utilisation of reclaimed wastewater are the gaining of public acceptance, as well as the associated cost for pipelines, pumping stations, etc. to convey the water from the wastewater treatment plant to where it is needed. Using spreading basins has the advantages of improving the quality of the wastewater through Soil Aquifer Treatment (SAT) and dilution with natural groundwater (Bouwer, 2002). Recharge and recovery also provides natural treatment, an essential ingredient in assisting with the acceptance of water reuse. Use of the reclaimed wastewater for irrigation of fodder crops is more easily accepted than irrigating crops for direct human consumption and use for potable supply. Higher levels of treatment and security of operation are needed progressively as the use of reclaimed wastewater approaches direct reuse.

Reclaimed water quality is primarily determined by the quality of the source water, the presence and nature of industries discharging wastes to sewers and the pre-treatment processes applied. Municipal wastewater is the most consistent in terms of quality. Constituents of potential concern include chloride, organic compounds, nitrogen species, phosphorus, pathogenic organisms and suspended solids (Committee on Ground Water Recharge, 1994). Toxic contaminants are mainly a function of the industrial effluent component of the wastewater. In the case of irrigation return flows to surface drainage systems, water quality may be affected by suspended solid, nutrients, pesticide residues, increased salt content and trace elements including selenium, uranium, boron and arsenic (Committee on Ground Water Recharge, 1994).

POTABLE WATER (EXAMPLE F)

Potable water is a major source of recharge water used in Aquifer Storage and Recovery (ASR) schemes. High-quality treated water is injected through wells, usually into confined aquifers to create a bubble of potable water in the aquifer. These bubbles can be created in non-potable aquifers by displacing the native water and have proved to be a cost-effective and environmentally sustainable method for resolving a wide variety of problems (Pyne, 1995). The schemes are usually constructed near treatment works, the source of the recharge water, to save cost and to utilise surplus treatment capacity.

In arid areas, such as the Gulf region of the Middle East, where water demand exceeds the availability of water from renewable resources, freshwater from desalination plants is used to bridge this gap. To ensure water availability during emergencies, for example, when desalination plants are out of commission, large freshwater storage capacities are required. Field trials have been undertaken to evaluate the feasibility of introducing desalinated water into aquifers to build up this freshwater reservoir (Mukhopadhyay and Al-Sulaimi, 1998). Due to the high quality of the desalinated water, no major geochemical compatibility problems are expected as the water can be treated to minimise any potential reactions with the aquifer material; for example the pH can be adjusted to be non-aggressive.

Hydrogeological settings and controls on recharge

The physical success of a Managed Aquifer Recharge scheme depends largely on the local hydrogeological conditions. These determine the ability of the recharge water to percolate through the unsaturated zone and the ability of the aquifer to store the recharge water.

The main factors to consider are:

- Physical and hydraulic boundaries of the aquifer and degree of confinement.
- Hydrogeological properties of the aquifer and overlying formations.
- Hydraulic gradient in the aquifer.
- Depth to aquifer/piezometric surface.
- Groundwater quality.
- Aquifer mineralogy.

The hydrogeological conditions at the surface and in the unsaturated zone are most important for schemes using spreading techniques, as water must move downward through these zones before reaching the aquifer. The percolation rate depends on the vertical permeability of the soil and unsaturated zone. Once the recharge water reaches the water table, the amount of water the aquifer is able to store depends on its hydraulic characteristics (transmissivity, storativity etc.) and its thickness and aeral extent. The receiving formation must have sufficient permeability and thickness to accept recharged water at a designated rate. On the other hand, aquifers with high hydraulic conductivities can result in rapid dispersal of the recharge water and, as a result, only limited quantities of water can be recovered. This may not be a problem if the aim of the recharge scheme is to supplement groundwater and base flow to streams on a regional basis.

Aquifers with low storage capacity may have only limited potential to accept additional water. High water tables may result in rapid transit of water to discharge points in streams and rivers, prolonging the period of flow of ephemeral streams. However, this is unlikely to be the case where groundwater is heavily exploited and groundwater levels are falling. In effect, storage capacity has been created that can be replenished by both natural and managed recharge.

Although there is a wide variety of hydrogeological environments; from the perspective of managed aquifer recharge, these can be grouped into four general categories, namely;

ALLUVIUM
(EXAMPLES B AND E)

Alluvium can consist of fluvial, marine and lacustrine deposits ranging in thickness from a few tens of metres to kilometres. Major deposits are usually found in the lower reaches of river basins forming flood plains. The topographic relief will usually be low, as will natural hydraulic gradients. The sediments will range from highly permeable coarse gravel to impermeable fine-grained silt and mud. Groundwater levels will naturally be shallow where the rivers are perennial, but may be at depth in arid regions or where pumping has lowered the water table. In the former case there is little storage space available in the aquifer and the resources in the aquifer need to be exploited, which may result in river water being induced into the aquifer.

FRACTURED HARD ROCK
(EXAMPLES A, C, F AND H)

This type of aquifer usually consists of fractured bedrock comprising igneous, metamorphic or volcanic rocks. These aquifers are found over large areas in semi-arid regions and despite having low storativity and transmissivity, they may be the only source of groundwater so careful management is needed. The weathered zone can play an important role in storage of groundwater as can alluvial cover, where present, as they provide a mechanism for absorbing and storing intermittent rainfall, which can then percolate to the underlying aquifer. In many areas the weathered zone is the main aquifer. Success in exploiting groundwater, as well as recharging aquifers, depends on locating these weathered or fractured zones where they are saturated. Abstraction from wells in the hard rock aquifer can drain the overlying alluvium/weathered zone seasonally. The appropriate recharge method will depend on which aquifer is targeted for recharge. If the unconsolidated alluvium is targeted, then infiltration basins or trenches may be most effective; however, if the deeper, hard rock aquifer is targeted then borehole injection may be the only option.

CONSOLIDATED SANDSTONE AQUIFERS

These are porous/fractured aquifers that can have good storage capacity and transmissive properties. The surface layer determines recharge, both natural and managed. If the soil is developed from the sandstone then recharge capacity will be high, but can be reduced if overlain by fine-grained alluvial deposits. If the permeability of the aquifer is high then recharged water is likely to be dissipated quickly and may be lost to base flow in rivers. A good understanding of the hydraulics of the aquifer is therefore needed to ensure that the net results of recharge are beneficial. It may be possible to manage the aquifer through annual overdraft in order to 'create' storage that can then be taken up by augmenting recharge during the wet season.

CARBONATE AQUIFERS (EXAMPLE D)

Similar arguments apply to carbonate aquifers as apply to the sandstone aquifers, except that the main storage and flow is in solution-enhanced fractures. The proportion of fracture flow to intergranular flow will vary considerably from low in porous limestone (e.g. oolites) to high in karstic limestone. The response of karstic aquifers will be the most extreme in terms of dissipation of recharged water and fast pathways for pollutants. Karstic aquifers can provide utilizable storage where groundwater flow is constrained, for example in a confined aquifer. Again, a good understanding of the hydrogeology of the aquifer, and the water resources it contains, is needed if they are to be managed effectively.

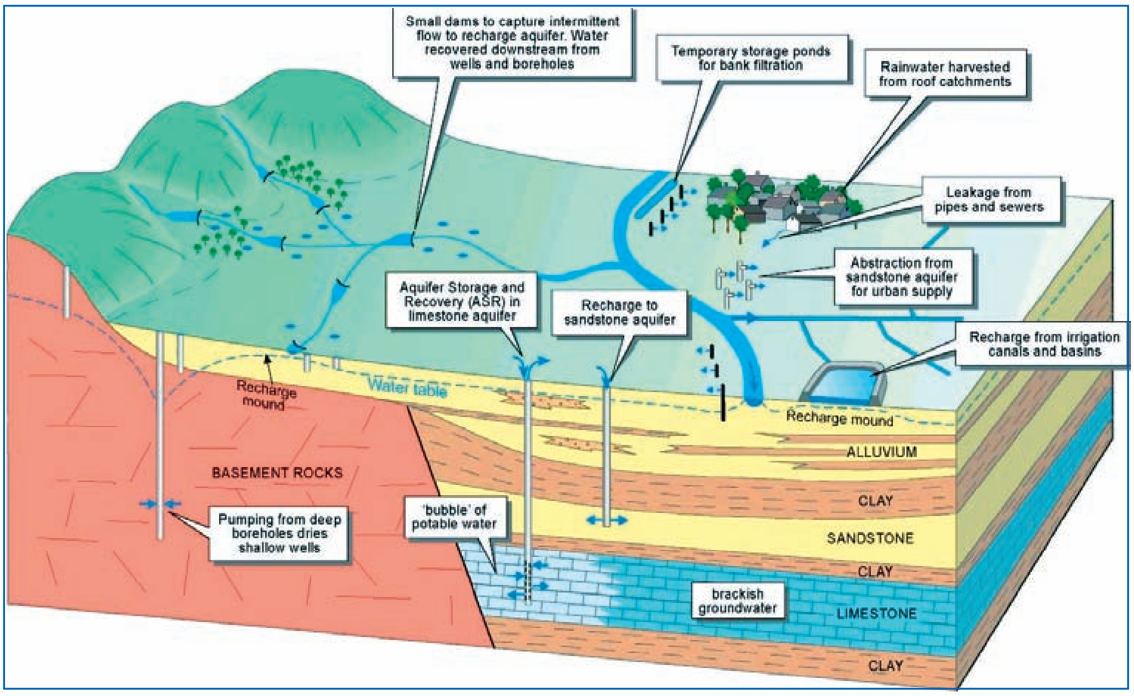
Methodologies for MAR

MAR techniques have been applied for millennia to manage available water resources. Methodologies range in complexity from simple rainwater harvesting to deep-well injection of reclaimed water into a saline aquifer. Methodologies applied should be appropriate to meet the defined objectives which, at the most basic level, will be storage and treatment of water. Clogging is a key issue that needs to be understood so the impacts can be minimised and managed in a cost-effective manner.

Numerous schemes exist to enhance recharge of groundwater and they are as varied as the ingenuity of those involved in their construction and operation. These schemes are designed with the prime objective of enhancing recharge (intentional recharge) but aquifers can also be recharged unintentionally (incidental recharge) whilst undertaking other activities, for example irrigation. Intentional methods are aimed at enhancing groundwater supplies but may also achieve other purposes, such as flood mitigation, reduced soil erosion or change of land use. Here we focus on intentional recharge, the methodologies applied being broadly grouped into the following categories, most of which are illustrated in the figure:

- Spreading methods
  - Infiltration ponds and basins
  - Soil Aquifer Treatment (SAT)
  - Controlled flooding
  - Incidental recharge from irrigation
- In-channel modifications
  - Percolation ponds behind check-dams, gabions, etc.
  - Sand storage dams
  - Subsurface dams
  - Leaky dams and recharge releases
- Well, shaft and borehole recharge
  - Open wells and shafts,
  - Aquifer Storage and Recovery (ASR)
- Induced bank infiltration,
  - Bank filtration
  - Inter-dune filtration
- Rainwater harvesting
  - Field bunds etc.
  - Roof-top rainwater harvesting

Many schemes require low levels of technology and can be (and have been for centuries) implemented with little engineering knowledge. This would include water-harvesting techniques to enhance recharge, field bunding and small bunds across ephemeral streams. Well digging skills have been developed over generations and diversion of surface flow into these (despite potential pollution problems),



subsequent to settlement of most suspended solids, is becoming increasingly popular in parts of India. Sand storage dams, spillways to river banks and perennial dams require more engineering design and knowledge, increasing further when using drilled wells and boreholes for injection or for Aquifer Storage and Recovery (ASR). Although simple in principle the efficient operation of spreading basins and infiltration schemes needs a good knowledge of the physical, hydraulic, geochemical and microbiological processes in operation and how to manage them for optimum performance. Similar issues need to be addressed in roof top rainwater harvesting.

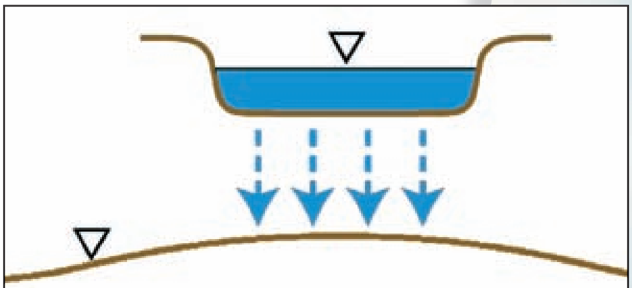
SPREADING METHODS

Water spreading is applied in cases where the unconfined aquifer to be recharged is at or near to the ground surface. Recharge is achieved by infiltration through permeable material at the surface, which is managed to maintain infiltration rates. In situations where there is a reliable source of good-quality input water, and spreading infiltration can be operated throughout the year, then hydraulic loadings of typically 30 m/yr can be achieved for fine texture soils like sandy loams, 100 m/yr for loamy soils and 300 m/yr for medium clean sands and 500 m/yr for coarse clean sands (Bouwer, 2002). Evaporation rates from open water surfaces range from about 0.4 m/yr for cool wet climates to 2.4 m/yr for warm dry climates so form a minor component of the water balance.

Where the source of water is sporadic from seasonal flow containing high loads of suspended solids, management of the recharge structure becomes increasingly important in order to minimize clogging to maintain infiltration rates and keep evaporation from open water to a minimum. Basic monitoring of the sedimentation rate and infiltration rate relative to the estimated rate of open-water evaporation will assist in operational management decisions.

Infiltration or recharge ponds or basins (Example B)

An infiltration basin is either excavated in the ground, or it comprises an area of land surrounded by a bank, which retains the recharge water (e.g. storm water), until it has infiltrated through the floor of the basin. If the aquifer material is fine, rapid clogging will occur. In this case, covering the bottom and sides with a layer of medium sand approximately 0.5 m thick can delay the clogging process and extend the recharge periods in the facility (Huisman and Olsthoorn, 1983). The same technique should be used on a fissured-rock aquifer, to prevent deep penetration of suspended solids or algae, which could result in irreversible clogging.


INFILTRATION POND

The depth of the basin should be shallow enough, to allow rapid draining in cases where cleaning of the basin by drying and scraping is necessary. Water levels should be managed to prevent growth of vegetation or accumulations of algae and consequent resistance to the flow of water. The area of land available for infiltration basins and the infiltration rate determines the volume of recharge achievable.

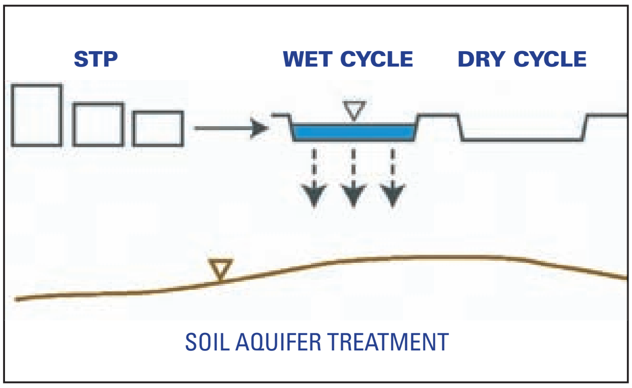
Clogging of the basin floor is the predominant problem during recharge, creating a filter skin on the bottom and sides of the spreading basin. To counteract this, the following methods should be considered:

- Apply a rotational system of water spreading and drying and subsequent scraping of the basin. Drying kills algal growth, and this, combined with scraping of the basin bottom, restores infiltration rates.
- Construct ridges on the floor of the basin and control the water level to winnow fines to settle in the troughs, thus maintaining infiltration rates on the sides of the ridges (Peyton, 2002).
- Mechanical treatment of the recharge water by primary sedimentation to remove suspended solids. Settling efficiency can be increased by addition of flocculating chemicals.

- Chlorination of the recharge water to inhibit microbial activity.
- Mechanical treatment of the soil by ploughing to increase permeability.
- Lining the basin with a layer of medium sand to act as a filter to remove suspended solids.

Soil Aquifer Treatment (SAT)

Planned reuse of water will become increasingly important as demand from users and the environment results in wastewater from sewage treatment plants (STP) becoming regarded as an asset rather than a disposal problem. Practical research undertaken over the last few decades (notably in Phoenix, Arizona led by H. Bouwer), has investigated hydraulic, operational and bio-geochemical processes involved in wastewater recharge and recovery through Soil-Aquifer Treatment (SAT). Inclusion of this cycle in the reuse process has several advantages including storage to smooth out supply/demand variability, quality improvements due to passage through the soil and aquifer, favourable economics and better public acceptance of water reuse (Bouwer, 2002). Sewage effluent being recharged via infiltration basins is usually treated to secondary levels and chlorinated before being applied to infiltration ponds. Water quality improvement is often the primary objective to remove all suspended solids and micro-organisms. Removal of nitrogen species through denitrification is also a key benefit, as is the reduction in concentration of dissolved organic carbon through biological processes. Phosphates and metals can also be removed but are retained in the soil.



The recharge water can be fully recovered to prevent contamination of natural groundwater and, as it is pathogen free can be used for crop, municipal and recreational irrigation. However potable use is constrained by residual organic carbon content, many synthetic organic chemicals. This needs to be addressed by treating the effluent with reverse osmosis or carbon filtration prior to SAT or by dilution with natural groundwater during recovery.

Controlled flooding (Example B)

In areas of relatively flat topography water may be diverted, with the help of canals, from a river and spread evenly over a large surface area. A thin sheet of water forms which moves at a minimum velocity to avoid disturbance of the soil cover. Highest infiltration rates are observed on areas with undisturbed vegetation and soil cover (Todd, 1959). In order to control the flooding process at all times, banks or ditches should surround the entire plain. As only minimum land preparation is necessary, flooding is very cost-effective compared to other spreading methods. However, large surfaces of land have to be made available for the recharge operation. High sediment loads will deposit on the surface and reduce recharge rates and remedial measures may have to be undertaken to maintain desired rates. Agricultural land used for flooding recharge can benefit from the sediment load, but this needs to be balanced against the reduced recharge rates (Esfandiari-Baiat and Rahbar, 2004).

Incidental recharge (Example H)

Excess irrigation water from canals and fields have historically caused water logging and salinization problems. However, where quantified and managed this incidental recharge can become and asset. For example, in the Indo-Gangetic Plain groundwater levels rose by about 6 m over a ten-year period and the water has been increasingly scavenged for irrigation water outside the surface water irrigation season. IWMI (2002) estimate that about 60% of the water applied to rice paddy is utilised, the balance percolating to groundwater. Recent studies have demonstrated that large canal irrigation systems can be modified to augment groundwater recharge.

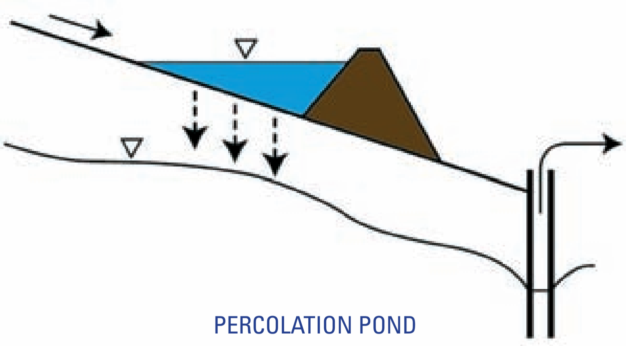
Groundwater quality issues arise when incidental recharge occurs from irrigation using urban wastewater. For example, use of municipal wastewater for agricultural irrigation is widely established in Mexico. Around cities such as Leon and Mexico City itself, groundwater levels are falling rapidly where abstraction to meet demand from a rapidly expanding population, exceeds recharge. However, where the wastewater is used for irrigation, the water tables are close to ground surface. The wastewater contains industrial pollutants of many types; in Leon the effluent from the tanning industry is a significant component. The main impact on the groundwater quality in the irrigated area is the presence of poor-quality water to depths of 50 to 100 m with chloride concentrations of 800 to 1000 mg/l in the upper portions. Many of the other pollutants in the wastewater are removed or attenuated in the distribution system and the soil zone. This helps to prevent pollutants such as organic carbon, nutrients, heavy metals and pathogens from reaching the groundwater body. The main threat to groundwater is increasing concentrations of chloride being drawn to the municipal supply wells in the area (Chilton et al., 1998).

It is also important to take incidental recharge into account in urban areas as it can form a significant component of the water balance of a catchment. Leakage from water, waste-water and storm-water systems in urban areas can contribute significantly to groundwater recharge, in some cases resulting in rising groundwater levels and flooding.

IN-CHANNEL MODIFICATIONS

Percolation ponds behind check-dams (Example A)

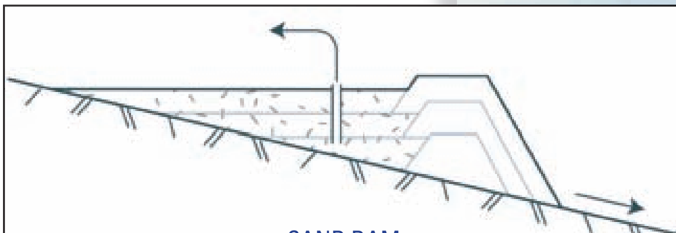
An inexpensive way of recharching water can be achieved by the construction of check-dams across a streambed with the construction material being in situ river alluvium. To avoid annual erosion or destruction of these structures a concrete spillway is often constructed and, to contain and channel surface runoff, bunds are also built. Associated field bunds retard the water flow to the stream and thus create an opportunity for this water to infiltrate into the ground as well as reducing soil erosion.



PERCOLATION POND

A series of these structures along a line of drainage will reduce the destructive energy of intense runoff (e.g. from monsoon rainfall), resulting in a reduction in erosion and sediment transport. As the water is only bunded in these structures for short periods, the land can be cultivated immediately afterwards in order to utilise the soil moisture and this can result in an additional annual crop. Tilling the land also maintains the infiltration capacity, in readiness for the next period of input.

In Kenya and many parts of India, surface weirs, and in Taiwan, inflatable dams, have been used to prolong the presence of water and increase the wetted area of alluvium in ephemeral streams.



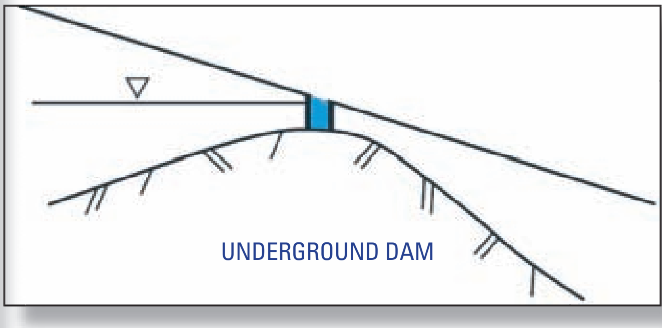
SAND DAM

Sand storage dams (Example G)

Sand dams are best sited in undulating terrain under arid climatic conditions, where runoff is often experienced as flash floods. The dams are typically constructed in sandy, ephemeral riverbeds in well-defined valleys. A dam wall is constructed on the bedrock, across the width of the riverbed to slow down flash floods or longer ephemeral flow events. This allows coarser material to settle out and accumulate behind the dam wall. The dam wall can be raised after each successive flood event, the height of the wall thereby determining the flood flow and the amount of material accumulating. However, sufficient overflow should be allowed for finer material to get carried away (Murray and Tredoux, 1998). Ideally, the dominant rock formation in the area should weather to coarse, sandy sediments; e.g. granites, sandstones, quartzites. With time, successive floods build up an artificial aquifer, which allows water to infiltrate rather than migrating downstream. Water stored is available for abstraction, however, sand storage dams can also be sited over permeable bedrock and thus replenish the underlying aquifer.

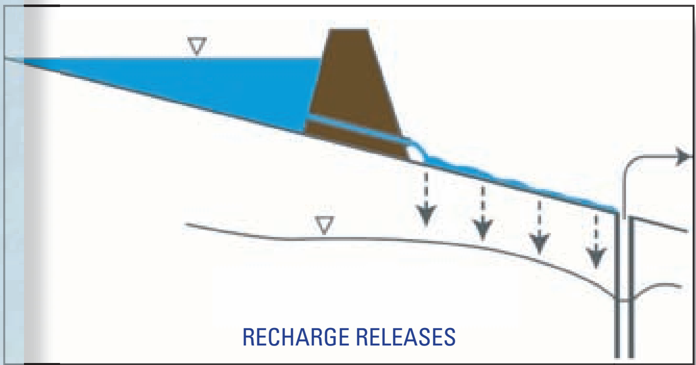
Subsurface dams

Subsurface (underground) dams may be used to detain water in alluvial aquifers. In ephemeral streams where basement highs constrict flow, a trench is constructed across the streambed keyed into the basement rocks and backfilled with low permeability material to constrain groundwater flow. The groundwater is recovered from wells or boreholes.



Leaky dams and recharge releases (Example C)

Where flow is very "flashy" and contains large amounts of suspended solids, the water may be lost to the catchment or to the sea before it can infiltrate to replenish the aquifer. Constructing dams on these ephemeral streams can address this problem by facilitating sedimentation. The water is then released through pipes to the downstream reaches of the river where groundwater recharge can occur. A good example of this practice is the OMDEL dam scheme in Namibia (Zeelie, 2002). A variance on this theme is the construction of leaky dams from rock-filled gabions with pipes running through the dam (Kahlown, 2004). These structures retain high-energy floods; stimulate settlement of suspended sediment and release of the water through leakage to infiltrate in the downstream riverbed.



WELLS, SHAFTS AND BOREHOLES

Open wells and shafts

These structures are used to recharge shallow phreatic aquifers and where the surface layers are of low permeability and hence spreading methods are not effective. Wells that have run dry due to falling water tables resulting from over-exploitation are increasingly being used for this purpose.

Settlement of the suspended solids in the recharge water is needed prior to recharge in order to reduce the potential for clogging of pores, particularly if the source is storm water. Subsequent abstraction may flush fines out of pores and go some way towards recovering the recharge capacity. Physical removal of sediment and jetting may also be required.

Use of wells has the potential to introduce not only suspended solids directly into the aquifer but also chemical (nitrates, pesticides, etc.) and bacterial (including faecal) contaminants. The spreading structures described earlier have the advantage, over open wells, of the water infiltrating from the surface passing through soil and alluvial deposits which can act as extremely effective filter/treatment mechanisms. Coarse material is sometimes used to fill pits or trenches to act as a filter and can be replaced if clogging becomes severe.

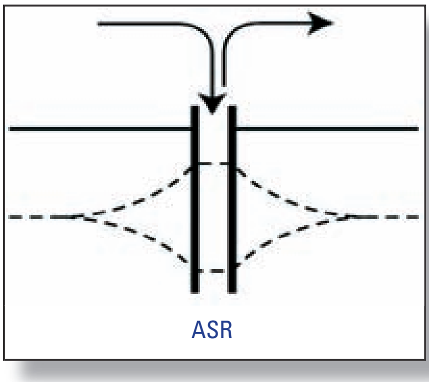
In loosely consolidated material, recharge pits and trenches are used in cases where low permeability material overlies the aquifer, which occurs at trenchable depth - approximately 5 to 15 m (Bouwer, 1996). Structures are excavated sufficiently deep to penetrate the low permeability strata, in order to provide direct access to the aquifer. Trenches or pits are built to maximise

Recharge pit constructed for recharge of surface runoff, Rajasthan, India the sidewall surface area and minimise the bottom surface area in order to facilitate horizontal movement of recharge water into the aquifer (Murray and Tredoux, 1998). Trenches can be backfilled with coarse sand or fine gravel and water is applied to the surface of the backfill. The facilities should ideally be covered to keep out sunlight, animals and people.

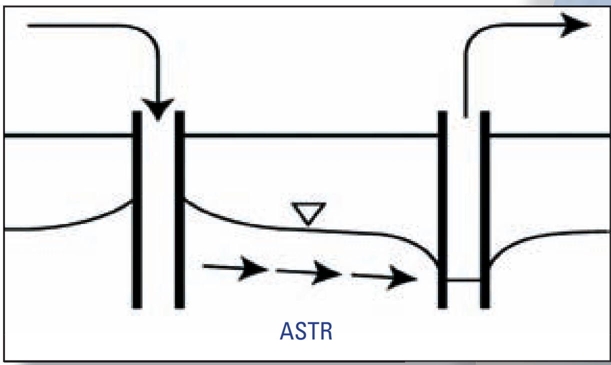
In general, pits and trenches are expensive to build and recharge small volumes of water, hence their use is mostly limited to those cases where they are already available in the form of abandoned quarries, gravel pits, etc.

Drilled wells and boreholes (Examples D, F and J)

Well or borehole recharge is used where thick, low permeability strata overlie target aquifers, in order to recharge water directly into the aquifer. Recharge wells are also advantageous when land is scarce. However, recharge water quality requirements are usually significantly higher for borehole injection than for groundwater recharge by means of spreading. A detailed description of this method is beyond the scope of this document, but can be found in Pyne (1995, 2005). Where the well/borehole is used for both injection and recovery (Aquifer Storage Recovery: ASR), costs are minimised and clogging is removed during the recovery cycle. Water can be injected into a borehole and recovered from another, some distance away, to increase travel time and benefit from the water treatment capacity of the aquifer. This is referred to as Aquifer Storage Transfer and Recovery (ASTR).



The technology needed to construct these structures can be quite complex, requiring some engineering skills. Design of structures can vary considerably and include the construction of boreholes in the base of wells and backfilling the well with graded filter material to (a) restrict the ingress of suspended solids that would rapidly clog the system; and (b) to restrict the



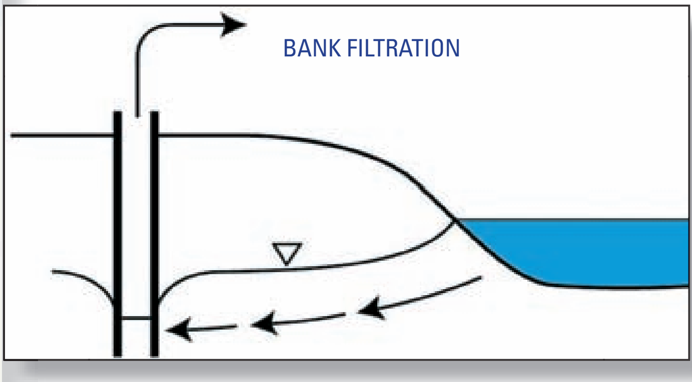
inflow of contaminants that might pollute the groundwater body.

Clogging of aquifer material or the borehole screen either by suspended sediment, entrained air in the recharge water, microbial growth or chemical precipitation is a common problem encountered, leading to excessive build-up of water levels in the recharge well. These clogging processes can be managed by mechanical treatment of the recharge water by sedimentation or filtration to remove suspended solids. Water should be introduced through a valve to ensure a continuous column to the surface. Some chemical pre-treatment of the water may be required to prevent flocculation of iron, $CaCO_3$, etc. and chlorination or other disinfection may be needed to prevent microbial growth. Clogged wells may need to be recovered at regular intervals using surging and pumping to remove fines and bacterial growth physically and the use of a wetting agent to remove air in an air-clogged well. Carbonate aquifers exhibit least clogging due to gradual dissolution of calcite by slightly acidic injectant, if periodic backflushing is observed.

INDUCED BANK INFILTRATION

Bank filtration (Examples E and I)

Riverbed infiltration schemes commonly consist of a gallery or a line of boreholes at a short distance from, and parallel to the bank of a surface water body. Pumping of the boreholes lowers the water table adjacent to the river or lake, inducing river water to enter the aquifer system. To assure satisfactory purification of the surface water in the ground, the travel time should exceed 30 to 60 days (Huisman and Olsthoorn, 1983), hence the distance for the water to travel should ensure this occurs.

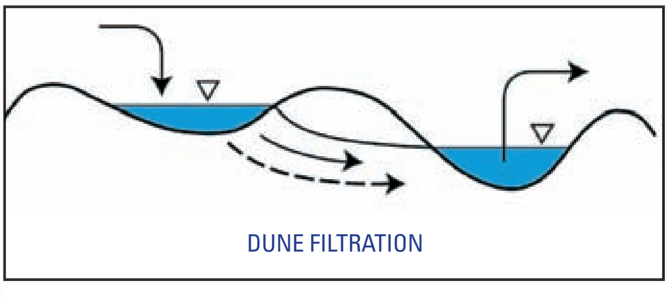


The factors controlling the success of induced infiltration schemes are a dependable source of surface water, of acceptable quality, and the permeability of the river or lake-bed deposits and of the formations adjacent to the surface water body (O'Hare et al., 1982). Provided that the permeability of the stream or lake-bed and aquifer are high and the aquifer is sufficiently thick, large amounts of groundwater may be abstracted from a well or a gallery without serious adverse effects on the groundwater table further inland (Huisman and Olsthoorn, 1983).

River and lake waters often carry a considerable amount of suspended matter, hence, if the water enters the aquifer this fine material filters out and leaves a layer of filter skin at the river/lake bottom. This provides useful treatment for infiltrated water but if clogging is excessive the surface may need to be scraped during periods of low water level.

Interdune filtration

A particular variant of this method is used in coastal zones and is known as inter-dune filtration. Here the valleys between coastal sand dunes are flooded with water from rivers to infiltrate into the underlying sediments and create a recharge mound. The mound can play an important role in preventing saline intrusion as well as providing a source of water that is abstracted further inland. This technique has been used for centuries and is highly developed along the coast of The Netherlands where rivers are the source of water for the recharge. In other schemes, storm and treated urban wastewater are the sources of water.



A key objective of these types of schemes is to improve the quality of the often poor-quality source water and much research has been undertaken to understand and optimise the management of suspended solids, clogging and the attenuation of dissolved solids, including organic compounds, using physical, chemical and biological processes.

RAINWATER HARVESTING

Rainwater harvesting, in its broadest sense is the collection of runoff for productive use. This usually involves the concentration of rainfall from a larger area for use in a smaller area as soil moisture or for recharging groundwater. Roof-top rainwater harvesting is a special case being increasingly used in urban areas for tank storage, urban irrigation and groundwater recharge.

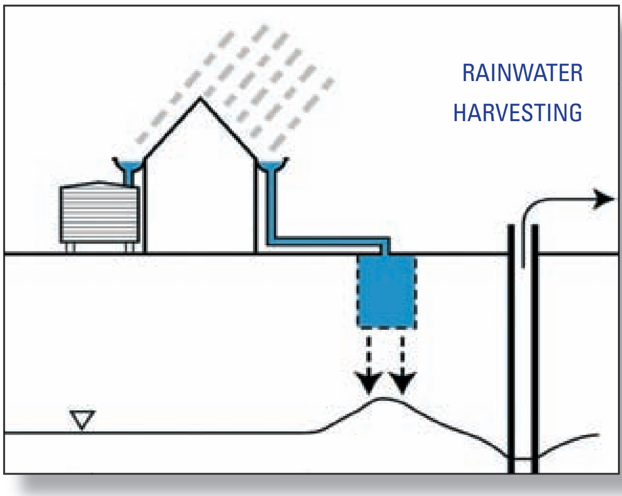
Dry land farming (Example G)

In semi-arid regions, dry land farming systems utilise between 15 and 30% of rainfall, the majority evaporating (30 – 50%) and the remainder going to surface runoff (10 – 25%) and groundwater recharge (10 – 30%) (van Leeuwen and Beernaerts, 2002). Interventions ranging from field bunds, contour ploughing and rock weirs in drainage channels to floodwater diversions into bunded cropping areas, all aim to reduce runoff and concentrate the water to be stored in the soil profile or the deeper aquifer. Whichever system is used, the aim is to significantly reduce surface runoff and evaporation in order to enhance agricultural production and, often unintentionally, enhance groundwater recharge.

Roof-top rainwater harvesting

Roof-top rainwater harvesting can conserve rainwater for either direct consumption or for recharge of groundwater. This approach requires connecting the outlet pipe from a guttered roof-top to divert rainwater to either existing wells or other recharge structures or to storage tanks. Drainpipes, roof surfaces and storage tanks should be constructed of chemically inert materials such as plastic, aluminum, galvanised iron or fibreglass, in order to avoid contaminating the rainwater.

Where the water is used for direct consumption, the initial water from a rainstorm is often allowed to run



to waste to flush accumulated dirt off the collection area and gutters. The main sources of contamination are pollution from the air, bird and animal droppings and insects. Bacterial contamination may be minimized by keeping roof surfaces and drains clean but cannot be completely eliminated. Advantages of collecting and storing rainwater in urban areas include the reduction of demand on water supply systems as well as reducing the amount of storm-water run-off and consequent flooding.

CLOGGING ISSUES

Settling of fine material and subsequent clogging of the aquifer is the main problem encountered in the majority of schemes described above. Clogging can be from suspended sediment load, microbiological growth, chemical precipitation and, in the case of ASR-type well injection, entrained air bubbles blocking pore spaces. A sound understanding of operation of the structure and the clogging mechanisms is needed for successful management. If the infiltration rate is of the same magnitude as the open-water evaporation rate then the value of the structure for recharge needs to be questioned. The situation can usually be managed by reducing the potential clogging problem prior to infiltration, together with periodic renovation of the infiltration surface through scraping, pumping or other physical or chemical means. Methods include:

- openings in sand dam walls through which water can flow during periods of low-flow at sufficient velocity to keep fine particles in suspension, allowing for silt free channels through the sand dam.
- Management of the catchment of the structure to reduce overland flow and soil erosion; e.g. through contour ploughing, gully plugs, preventing overgrazing, planting to stabilize soil etc.
- Construction of siltation ponds upstream of the facility to allow fine particles to settle out before the recharge water is applied to the dam, spreading structure or open well. This can include the construction of leaky dams and recharge release dams.
- Because the infiltration area is small in injection wells, the water quality has to be particularly high and may require sand filtration and degassing as well as disinfection if clogging problems are to be managed.
- Wastewater with high nutrient loads have to be treated to remove suspended sediments and the nitrogen species, managed through alternating wetting and drying cycles. See SAT (Bouwer, 2000).
- Periodic removal of sediment through scraping to avoid fine material from penetrating too deeply into the infiltration surface.

The costs of these management and maintenance programmes have to be met and justified against the benefits of the infiltrated water. If the recharge structure is a communal venture then those who benefit most need to bear the majority of the costs.

Institutional issues in MAR schemes

Even if the hydrological and hydrogeological parameters of a recharge scheme are favourable, the success of a scheme cannot be assured unless it is managed and operated effectively. The major institutional issues relate to planning and objective setting, and the implementation and management of agreed recharge activities.

A variety of approaches have been employed for implementing natural resource management activities such as MAR, with responsibilities resting (to varying degrees) with the state, local government, development agencies, the private sector, NGOs and local people. In this section, we focus on decentralised, low cost recharge activities, often organised through state/government – NGO partnerships.

A dominant institutional theme emerging over the last two decades has been decentralisation, often in tandem with efforts to promote a more 'bottom-up', participatory planning process. This has been the case in India, for example, where watershed development programmes, often with a strong MAR focus, have increasingly stressed the need for participatory, decentralised decision-making. As the poor are disproportionately dependent on common pool resources such as water, so the argument goes, improvements in decentralised management - whether in equity of rights and responsibilities, in resource productivity, or in its sustainability – can contribute substantially to their livelihoods (Carney and Farrington, 1998).

Decentralisation and participatory management are clearly linked. Participatory management can be defined as a process whereby 'those with legitimate interests in a project both influence decisions which affect them, and receive a proportion of any benefits which may accrue' (ODA, 1995). It is now generally accepted that to enhance and sustain the productivity of natural resources, those engaged in and affected by managing the resource must participate in planning its rehabilitation and management. As Farrington et al (1998) point out, this implies new ways of doing business – channelling funds; managing projects; taking decisions etc- for a range of stakeholders involved in building the new coalitions. It also implies changes in the locus of decision-making power and access to resources. Despite its 'feel good' overtones, therefore, participation is not a neutral concept: vested interests and existing power relations are challenged, and the new ways of doing business are often highly contested.

A key concern for MAR, whether carried out in isolation or as part of a wider package of resource management measures - is to identify approaches that ensure the interface between rural people, local organisations and the state is managed in a way most likely to enhance efficiency, effectiveness and accountability (Carney and Farrington, 1998). Looking specifically at stages of the project cycle, and drawing on experience of MAR within watershed programmes in India, the following issues are worth highlighting.

Key issues at the **planning objective setting** stage relate to the need for clarity over the objectives of MAR, and how (and by whom) objectives are defined. Of particular concern are the views and interests of different groups – including those in downstream parts of a catchment, and those without land and private water sources - and the extent to which objectives have been locally defined and agreed. Experience indicates that better performing projects engage local people in a discussion about what their problems and priorities are (e.g. reliable drinking water supplies; supplementary irrigation), what different groups value most, and adopt flexible approaches to diverse livelihood systems and physical conditions.

Related questions concern the extent to which decisions are made with, or on behalf of, local people about:

- Area/community selection or eligibility
- Participation responsibilities (e.g. for construction, cost-sharing)
- Technical options (e.g. for the design and location of structures)

Again, experience indicates flexibility and joint decision-making are key: projects that devote time and resources to consulting and organising local people, and that clearly define the obligations and responsibilities of different groups (e.g. around maintenance) perform better over the long term.

It is important to consider the distributional and equity issues around MAR at the planning stage. An assumption that recharge activities will benefit everyone, equally, is unlikely to hold true with uneven patterns of water access and water rights. A project may therefore need to consider how broad costs and benefits are likely to be distributed between:

- Different social and wealth groups. For example, who should contribute towards costs

THE EVOLUTION OF WATERSHED DEVELOPMENT PROGRAMMES AND MAR IN INDIA

In India, MAR in rural areas is typically carried out as part of a package of measures aimed at developing, or rehabilitating watersheds. Such watershed development programmes combine a range of land development/ protection, soil moisture conservation, afforestation, pasture development and horticultural activities, as well as explicit water resource conservation/augmentation measures.

Watershed development projects, in various forms, have been operating in India since before Independence. However, the main stimulus to government action occurred in the 1970s and 1980s when long term field experiments confirmed that introducing physical barriers to soil and water flows, together with re-vegetation, could generate significant increases in resource productivity. These experiments catalysed the formation of numerous government projects, schemes and programmes, under a range of government departments, to support micro-watershed development.

Early watershed development programmes took ecological objectives as their starting point. Ecological objectives, set through physical targets, defined the scale and scope of watershed projects, and projects were managed as public works with only limited local participation. Reviews of early projects indicated limited success in meeting environmental and (assumed) livelihood objectives, with only a small minority of projects - those managed by NGOs and other locally based agencies - demonstrating sustainable outcomes for poor people (Kerr et al, 1998).

This approach changed markedly in the mid 1990s, mirroring wider shifts in water sector policy aimed at promoting a more people-centred planning approach. In particular, there was a shift away from physical targets to the rehabilitation and development of environmental resources in an integrated manner to develop economic resources and reduce poverty. In terms of strategy, emphasis was placed on participatory approaches that involved local communities in both the planning and implementation of interventions. Many of the changes were catalysed by a progressive set of guidelines (often termed 'the Common Guidelines') for watershed development issued in 1994 by the (then) Ministry of Rural Areas and Employment. The guidelines marked a significant shift in approach in several important respects (after James and Robinson, 2001):

- In encouraging the development of partnerships between government and non-government organisations as Project Implementing Agencies (PIAs), including NGOs.
- In decentralising the management of programmes to local government, where possible, and to PIAs.
- In facilitating the participation of local people in the design and implementation of watershed rehabilitation activities, including Managed Aquifer Recharge, through especially appointed Watershed Committees.
- In allowing local control over the disbursement of central funds for rehabilitation, through District Rural Development Agencies.

Presently, micro-watershed management absorbs over US$500 million per year, channelled mainly from central government sources. Donors have shown considerable interest in watershed development, not least because it offers the potential to put Integrated Water Resources Management (IWRM) principles into operation, including water conservation and supply augmentation, with support for rural livelihoods. Nonetheless, while most watershed development programmes stress the importance of MAR, there are no 'quick fixes' to emerging over-exploitation threats, and certainly not without action to constrain water demand.

Source: based on Gale et al, 2002.

given the likely, or predicted, project beneficiaries?

- Different areas. How will downstream water users be affected, for example, if excess surface flows are now recharged upstream? The impacts of recharge activities – both positive and negative – are not likely to be constrained within community boundaries.
- Different time periods – are there short and longer-term winners and losers?

Key issues around **implementation and management** relate to the composition and capacity of local management organisations, and the design and operation of cost-sharing arrangements.

In terms of management organisation, the establishment of user committees around recharge structures themselves, or around watershed development activities more generally, may be a precondition for project assistance. Community management often implies that the community should commit resources towards the implementation and upkeep of infrastructure, whilst benefiting through the exercise of authority and control over management of the system. The commitment of users to a recharge activity or project can be demonstrated in a number of different ways. For example, contracts, upfront cash payments, and contributions of labour and/or materials for construction can all be used to confirm user demand for a system, and to indicate to project staff, or government, that planned activities match user expectations. Projects which devote time to community mobilisation and user group formation, and that clearly define their rights and responsibilities, are likely to be more sustainable.

In terms of cost-sharing arrangements, rules regarding asset ownership, operation and maintenance and ongoing recovery of system costs should be established during the planning phase and agreed upon by all stakeholders. Rules need to be transparent, with a clear process for setting, reviewing and adjusting contributions over time. Again, the potential impact of a project on poorer households should be addressed by a project before a contribution system is implemented, and any subsidy arrangements agreed. Flexibility is important. In contributing to the capital costs of a recharge scheme, for example, poorer households could be allowed to increase their labour contribution in return for a lower cash payment.

As noted above, issues around who pays and who benefits from a recharge activity also require definition though, as noted in the technical briefs of this booklet, it is not always easy to predict the impact of MAR on groundwater conditions, and people's access to water, in a specific area.

Concluding remarks

- Managed Aquifer Recharge (MAR) is increasingly being used to manage and store water. There are many methods that have been developed over the centuries depending on source and availability of water, demand, geology and socio-economic structure. These methods are being widely reapplied and developed using current technologies but examples of quantified assessments of their effectiveness are limited.
- Improved understanding of how recharge structures actually work and the impacts they have on water availability, water quality, social and economic sustainability as well as the local and downstream environment, needs to be gained and disseminated to promote widespread cost-effective implementation.
- Managed Aquifer Recharge must be regarded as a part of an integrated water and catchment management strategy along with surface water and soil management, erosion and pollution control as well as demand and environmental management and wastewater reuse. Its role will become increasingly important as demand increases and the impacts of climate change and variability become more apparent.
- Promotion of Managed Aquifer Recharge should focus on sharing knowledge through networks and demonstration projects of good practice, supported by a range of training initiatives including on-line resources, courses, seminars and workshops.

Examples of managed aquifer recharge schemes

In order to illustrate some of the issues discussed in this report, a selection of example schemes from a range of hydrological setting and using a range of water sources, have been gathered. The brief summaries given below provide a link to further documentation, the source documents being cited. In addition, there is a list of key reference documents listed at the end of the report and further information and examples can be found on a searchable database at www.iah.org/recharge.

A. WATERSHED MANAGEMENT IN RAJASTHAN, INDIA.

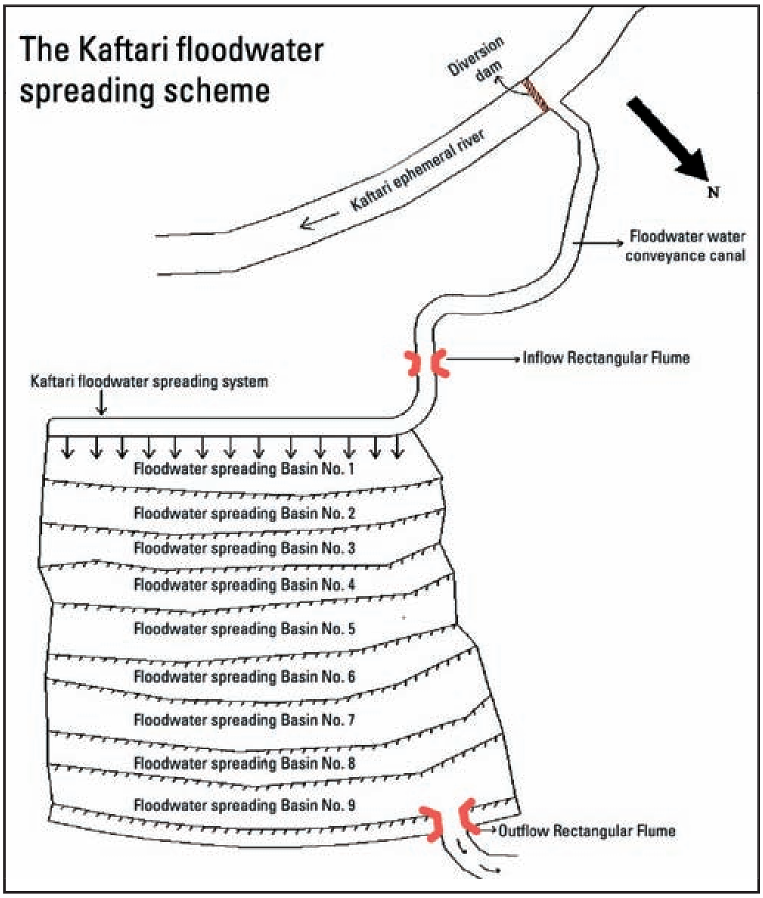
In 1985, the Arvari River catchment (in common with other catchments in the area) was in a highly degraded state due to over-pumping of groundwater, removal of natural vegetation and soil erosion, compounded by severe drought. Lack of even the most menial employment resulted in migration from the area. The NGO, Tarun Bharat Sangh (TBS) tackled the problem of lack of secure water by initiating a programme of water harvesting by constructing crescent-shaped earthen dams – Johad – to capture rainwater running off the surrounding hills during brief but intense storms. Rainwater harvesting over the next two decades, was accompanied by soil-water-forest conservation programmes, designed and implemented by the people in the area. Financial and advisory support was provided by TBS, under the leadership of Rajendra Singh. Progress was made by popular agreement. For example, the farmer providing land for the *Johad* to be constructed on would be the prime beneficiary of the recharged water on adjacent land. However the larger community would also benefit.

Implementation of schemes by an increasing number of villages in the area through example has resulted in over 70 villages now being involved in the scheme, constructing many thousands of Johads and other water-harvesting structures. The "Arvari River Parliament", formed by the people for the purpose, currently undertakes management of the catchment. The increased recharge combined with the other watershed management initiatives have resulted in rising groundwater levels and, since 1995, perennial flow in the Arvari River.

REFERENCE: Arvari. Information VCD issued by Centre for Science and Environment, India. www.cseindia.org

B. AQUIFER RECHARGE USING A SPREADING SYSTEM, KAFTARI, IRAN

Overexploitation of groundwater has caused significant drawdown of the water table (1.5 m/year) and deterioration of groundwater quality in the Dorz-Sayban Plain, which is located 115 km to the southeast of Larestan, Iran. 3500 hectares of land are irrigated using groundwater in this



plain. To decrease the rate of drawdown of the water table, five floodwater-spreading systems for recharge of groundwater were designed and constructed in the region between 1983 and 2001.

Inflow and outflow rates from the Kaftari floodwater-spreading system were measured for nine flood events during 2002-2003 using rectangular flumes in the system. The maximum inflow and outflow rates of the system were 20.3 and 7.26 m^3/s, respectively. The total volume of inflow and outflow of the system were about 886,000 and 146,000 m^3 for the 9 flood events. Therefore, 83.5% of the inflow to the system was recharged to the aquifer, only small quantities being lost to evaporation. This shows the high performance of floodwater spreading systems in the recharge of groundwater.

More than 70% of the suspended load has settled in the system. This will inevitably lead to clogging and reduction in efficiency of the system but also an improvement of the soil for agricultural purposes. Additionally, the managed aquifer recharge improves the quality of groundwater, as the EC of the floodwater is much lower than that of the groundwater (0.3-0.4 vs. 2.0-9.0 dS/m).

REFERENCE: Esfandiari-Baiat, M and Rahbar, G. 2004. Monitoring of inflow and outflow rate from Kaftari artificial recharge of groundwater system in dorz-sayban region in South-eastern Iran.

C. LEAKY DAMS TO REPLENISH DEPLETING AQUIFERS IN BALOCHISTAN

Groundwater is the only reliable source of freshwater in Balochistan. Its use has increased many-fold due to expansion of agriculture, rapid growth of population and industry during the last two decades. Groundwater withdrawal from aquifers greatly in excess of recharge has resulted in drying up of many dug wells, springs, and karezes; the situation has been further aggravated by the recent extended drought (1998-2002) in the province.

The Pakistan Council of Research in Water Resources (PCRWR) introduced and implemented the concept of constructing and operating leaky dams in Balochistan under one of its research and development projects. The first leaky dam was constructed during 2002 at Margat about 35 kilometres from Quetta. A groundwater-monitoring network consisting of 7 piezometers was installed to monitor effects of the dam.

The leaky dam acts as a barrier reducing the velocity of water runoff and retaining water for sufficient time to allow the sediment load to settle to reduce clogging of the macro pores in the

Leaky Dam Balochistan, downstream

Xerophytic shrubs planted in catchment

downstream bed. This increases rainwater movement into the aquifer and storage below the ground surface for future use, thus minimising evaporation losses, which are high in upland Balochistan.

The construction of low cost leaky dams and check dams with leaky embankments is made with boulders, cobbles, stones and large size gravels available within and around the streams and rivers. The dam materials are held within wire mesh nets built in 5 steps to a total height of 4.9 m. Pipes are incorporated on top of the 2nd and 4th steps to discharge surplus water for infiltration downstream. The top of the dam acts as a spillway and upstream and downstream aprons are constructed to prevent erosion. The dam has a catchment area of 1.79 km^2 and a storage capacity of about 11000 m^3.

Although, the quantitative impact of leaky dams will only be determined with the passage of time, the introduction of the concept has been appreciated and acknowledged by professionals and farmers. Such technologies will be evaluated, refined and implemented to increase groundwater recharge.

Already the design of the dam has been improved. The need has been identified for a small size gravel-filled adjustable sheet to be placed on the upstream side of the dam body. This is to allow for longer retention time of rainwater in the reservoir prior to permitting the slow release of water for recharge in the streambed.

Implementation of this technology must be accompanied by other interventions. These include the strict protection and complete control of grazing along with extensive watershed management in the catchments to reduce the sedimentation load in the reservoirs as well as enhancing the natural recharge of precipitation. In this case this has included the planting of 600 shrubs of 3 Xerophytic species in the catchment area. Indiscriminate cutting and uprooting of range-land shrubs, grasses and trees must be discouraged by creating alternative energy pools i.e. subsidized supply of LPG, natural gas and fuel wood. The subsidies in the form of electricity flat rates, connection of electricity for tube wells to the farmers should be linked with adoption and making of recharge structures as well as watershed management practices.

REFERENCE. Kahlown, M A. 2004. Leaky dam to rejuvenate depleting aquifers in Balochistan.

D. STORING STORM WATER RUNOFF IN BRACKISH AQUIFERS USING BORE-HOLE INJECTION TO DEVELOP IRRIGATION WATER SUPPLIES – AUSTRALIA

Development of irrigation water supplies by injecting storm water runoff in brackish aquifers is practiced in few places in the world, but may have much wider applications, especially in semi-arid regions. Examples from South Australia demonstrate the technical and economic feasibility, and environmental sustainability of artificial recharge and recovery of storm water for peri-urban irrigation water supplies.

A major driver for water re-use via aquifers is the need to protect the marine and freshwater ecosystems into which storm water and treated effluent is conventionally disposed. The trend toward more stringent load or concentration limits for discharge means that more advanced catchment management and improved treatment methods give greater opportunities for aquifer storage and recovery.

The quality of water suitable for injection into aquifers for reuse is defined by meeting three objectives:

- Irreversible clogging of the injection well needs to be avoided.
- Existing and potential beneficial uses of groundwater need to be protected.
- The quality of the recovered water needs to meet the requirements for its intended uses.

New guidelines for the quality of water to be injected into aquifers in Australia have recently been developed taking account of these objectives. These guidelines differ from those in use in other countries for two reasons: (1) they consider beneficial uses in addition to human consumption, and (2) they take into account sustainable treatment occurring within the aquifer. The guidelines conform to the principles of the Australian National Water Quality Management Strategy, and refer to the relevant water quality guidelines to determine fitness for each beneficial use (or environmental value).

Where urban areas have clay soils, such as most of metropolitan Adelaide, until recently little urban storm water runoff was retained and drainage schemes accelerated its discharge into the sea. Limestone aquifers are present beneath the city, but cannot be economically connected to storm water by detention ponds or spreading basins because of the low seepage rates through the surficial clay.

However when holes are drilled 100 or so meters to penetrate these underlying limestone aquifers, the connection is made, and winter runoff can be stored until summer using the aquifer as an underground reservoir. Urban runoff is collected and treated in detention basins and wetlands which are constructed to reduce flood risk and to improve the quality of storm water and receiving waters. The detained water is then fed by gravity or pumped into the injection well via basic treatment systems such as screens or filters. The recovered water generally requires no treatment when used for irrigation.

The study site is located in a new suburban development, known as Andrews Farm, on the northern fringe of the Adelaide metropolitan area. The water source for injection is storm water runoff derived from a peri-urban surface water catchment (residential and sheep grazing), which covers an area of 55 km^2.

The uppermost 19 m of a confined Tertiary aquifer, situated at a depth of 105 metres below ground surface was targeted for injection. Three observation wells were drilled at distances of 25, 65 and 325 metres down gradient of the injection well. The aquifer is comprised of variably cemented fine carbonate and sand material, with a transmissivity of 180 m^2/day and storage coefficient of $5x10^{-4}$, measured by aquifer pumping tests (Gerges *et al.*, 1996).

Ephemeral storm water runoff is held in a detention basin, and pumped via a screen and the injection well into the aquifer. In the period from August 1993 to March 1997 there were five major injection seasons. The first using mains water and the remainder were storm water. A total of approximately 240 000 m^3 of water was injected. The rate of recharge varied between 15 and 20 L/s.

Following injection, only faecal coliforms (on occasions), may exceed the guideline for irrigation water. Faecal coliforms exceed the guidelines for drinking water (National Water Quality Management Strategy, 1992) in the post-injection waters, although they die off to levels, which are acceptable with respect to these guidelines within a period of four weeks (Pavelic *et al.*, 1996). Studies are underway to assess the survival of pathogens which are more long-lived than coliform bacteria (Toze, 2005).

All other parameters have little or no detrimental impact on groundwater quality, and often have a beneficial impact (eg. TDS). Note that prior to injection, groundwater did not meet the drinking water guidelines with respect to total dissolved solids and iron. Of the trace organic compounds monitored, only atrazine (a common herbicide) and pentachlorophenol (a commonly used wood preservative), were detected in storm water and observation wells at levels substantially below the drinking water guidelines.

Various forms of clogging have been encountered as a result of storm water injection. The earliest, and most easily recognisable was by zooplankton, which was the only form of clogging to halt injection. This was alleviated by shielding the pump intake with a filter fabric (Gerges *et al.*, 1995). Some suspended sediments accumulate around the large contact area at the injection well and aquifer interface. Because the particle size range of the injectant (median ~4 mm) is much smaller than that in the aquifer (median ~120 mm), most of the injected particulates penetrate the aquifer and possibly settle at larger radii from the injection well, but this has yet to be confirmed. Hekmeijer, (1997) showed that physical clogging causes some head build-up around the injection well, but not of significant concern to the operation. Clogging can be overcome by effective redevelopment of the injection well by airlifting (Pavelic et al., 1998). After the early zooplankton problems, which required the well to be more frequently redeveloped, experience was gained to enable this to be extended to once or twice a year. Monitoring of the suspended sediment load, along with the particle size distribution of the sediments extracted during airlifting shows that a very small proportion of these (~1%) are derived from the storm water. Most extracted sediments are derived from the sands of the aquifer matrix, which are mobilised as calcite dissolves (Rattray *et al.*, 1996). Organic matter is filtered around the injection well resulting in growth of bacteria, which may contribute to clogging in the short term.

Results from this pilot study, the first well-instrumented and monitored ASR site to use detention basin treated storm water in Australia, shows the facility is capable of providing water suitable for irrigation. It is possible that with the treatment provided in the aquifer, a drinking water supply could ultimately be developed. As with many pilot experiments, technical problems have been encountered, but have been overcome.

REFERENCE: Martin, R.R., Gerges, N.Z. and Dillon, P.J. (2000) Aquifer Storage and Recovery (ASR) using water treated to irrigation standards. Proc. 30th IAH Congress, Cape Town, South Africa.

E. INTER-DUNE RECHARGE IN ATLANTIS, S. AFRICA

Atlantis, a town situated on the west coast of South Africa, about 50 km north of Cape Town, meets its potable water demand of approximately 5.5 x 106 m^3/a entirely through managed recharge of a shallow sandy aquifer. The climate of the area is Mediterranean, with mean maximum and minimum temperatures of 23.3°C and 11.8° C, respectively. The mean annual precipitation is around 450 mm, however about 65% of the rainfall events occur during the winter months of May to September.

Extensive deposits of Cenozoic sediments, which constitute an unconfined sandy aquifer, underlie the area. The total sand cover reaches a thickness of 60 m in the central area, with an average thickness of 25 m. These sediments are underlain by shales and greywackes, while the upper surface area of the aquifer is covered by either mobile sand dunes or vegetated sands. Due to rapid facies changes over short distances, the aquifer is inhomogeneous, anisotropic and phreatic to semi-unconfined and transmissivities range from 50 to 1300 m^2/d.

Currently, withdrawal of water from the Atlantis aquifer is restricted to two well fields. Two large recharge basins, covering an area of approximately 500,000 m^2 when full are situated some 500 m up gradient to recharge the aquifer. Three sources of water are available for recharge, namely storm water runoff, groundwater and treated wastewater. The storm water is collected in detention basins. A system is in place to divert poor quality storm water from industrial zones away from the recharge basins to dispose the water in a coastal recharge basin. Groundwater is extracted from the sandy aquifer at two well fields, treated in an ion-exchange water-softening plant, distributed, utilised, collected, treated and recharged together with the urban storm water runoff.

To be able to use wastewater as a recharge water source, a sewerage reticulation system has been implemented, which allows the separation of sewage from the residential and industrial areas. The domestic wastewater is treated in activated sludge works and blended with “domestic” storm water before being discharged into the recharge basin. Treated industrial effluent and storm water collected from industrial areas is not considered re-usable for town supply and is disposed of in a series of coastal infiltration basins. This provides an environmentally acceptable way of disposing of poorer quality water and also forms a barrier between the wellfield and possible saline intrusion from the sea.

The low clay content of the alluvial aquifer constrained purification processes during infiltration and solutes like potassium could be traced over substantial distances down gradient from the recharge basin. Careful control of the quality of the water being discharged into the recharge basin is needed to improve the recharge water quality. However, that is only possible by compromising on the quantity of water being recharged. If the recharge basin receives the maximum available water, the groundwater quality deteriorates severely. If only the best quality water is being recharged, the volume reduces greatly, but the groundwater quality improves. Different management strategies produce distinct recharge water-quality signatures that can be detected in the groundwater. Hence, flexibility has been build into the scheme to enable management to include or exclude the various recharge water components, as dictated by water quality needs and supply demands.

Managing water quality and, in particular, salinity has been one of the greatest challenges for the Atlantis Water Scheme. 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.

Production borehole clogging 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.

Enhanced groundwater recharge ensured the sustainability of the Atlantis water supply over two decades and will continue to play a key role. The scheme is highly cost-effective and can sustain continued urban growth of Atlantis well into the 21st century. The scheme is able to deliver water at a cost of 20 % of what it would have been, if piped surface water would have been used for the supply of portable water for Atlantis, as proposed at an earlier stage. Atlantis serves as a prototype for further development in the arid areas of southern parts of Africa.

REFERENCE: Tredoux, G., Murray, E C. and Cave, L C. 2003. From Chapter 8. Infiltration systems and other recharge systems in Southern Africa. "Management of Aquifer Recharge and Subsurface Storage." NCC-IAH Publication. No. 4.

F. RECHARGING FRACTURED QUARTZITES IN WINDHOEK, NAMIBIA

Windhoek is located in the semi-arid central highlands of Namibia. Up until 1970, with the completion of a major water supply dam, the Windhoek aquifer was the city's main water source. Now the aquifer is a back-up source for surface water and an emergency source during periods of drought. The reliability of this source has, however, been compromised as a result of large-scale abstraction since the mid-1900's.

The city depends primarily on surface water, but due to unreliable rainfall, reserves in the supply dams regularly run low. Groundwater currently accounts for 10% of the city's water needs, but with large-scale managed aquifer recharge this could be increased significantly - to the extent where the aquifer (or water bank) becomes the city's main water source during droughts.

The Windhoek aquifer consists primarily of quartzites and schists. The geological setting is extremely complex due to several episodes of folding and faulting, including thrusting and rifting. The intense faulting together with the contrasting physical and mineralogical characteristics of the schists and quartzites has resulted in a highly fractured and anisotropic aquifer system.

The ability of the aquifer to receive water at a high enough rate to make the project economically worthwhile was established by conducting borehole injection tests. The longest test lasted 195 days and the highest injection rate achieved was 59.4 L/s (214 m^3/hr). The injectant, although fully treated drinking water from Windhoek's water supply

Erecting a granular activated carbon filter next to an injection borehole , Windhoek, Namibia.

dams, was further treated with granular activated carbon and chlorination. This is to ensure that only water of very high quality is transferred to the aquifer, and that long-term clogging risks are minimised.

The City of Windhoek adopted a 3-phased approach to implementing large-scale artificial recharge. The 1st phase, using existing boreholes, has already been constructed. It has an injection capacity of 3.7 Mm^3/a. The 2nd phase (also using existing boreholes) will increase the injection capacity to 8.1 Mm^3/a; and the 3rd phase (with new injection boreholes in the outer reaches of the aquifer) could provide infrastructure to inject 16.5 Mm^3/a, or 90% of the city's current annual water requirements. The long-term goal is to be able to replenish the aquifer as rapidly as possible after periods of high abstraction.

REFERENCE: Murray, E C. 2004. Wise water management for towns and cities. Water Research Commission, S. Africa. (www.wrc.org.za) ISBN 1-77005-092-2.

G. SUBSURFACE WATER STORAGE IN KENYA

There is increasing pressure on land in Kenya, in arid and semi-arid areas where rainfall is erratic and water loss due to runoff is high. 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.

The cost of a 60 m^3 sand dam in Kitui with a minimum design lifetime of 50 years and a minimum yield of 2,000 m^3 is 6,000 Euros. This is equivalent to six 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 six tanks, which would serve only six households.

REFERENCE: Mutiso, S. 2003. From Chapter 4 of "Management of Aquifer Recharge and Subsurface Storage." NCC-IAH Publication. No. 4.

H. AQUIFER RECHARGE BY IRRIGATION CHANNELS IN THE SOUTHERN SIERRA NEVADA, SPAIN

In southern Spain, every year between March and June, when surplus water is available due to the snowmelt, river water is diverted by way of an extensive network of irrigation channels to well defined, highly permeable areas.

The area is underlain by hard rocks, mainly schists, secondary quartzites and limestones. Managed recharge is practiced by a network of irrigation channels, which gently descend, following the contour lines of the slope. The channels are dug into the soil and are unlined and up to 15 km in length.

Water infiltrates in zones of high permeability, which is either the weathered overburden or fracture zones in the host rock. Ditches to the irrigation channel specially connect some favourable fractures in the host rock. Fractures used for infiltration have openings of up to 10 cm. Due to the recharge activity in the area, two types of springs developed. Temporary springs emerge, where subsoil water circulation is observed. The flow regime is directly related to the irrigation process and dries up, as soon as the irrigation channel has dried up. Water, which enters the fractured host rock, also discharges in perennial springs in the area. Flow is maintained all year round, but can decline considerably after long periods without recharge. The transit time between infiltration point and the different springs has been established by tracer tests and is about five days for water circulating at shallow depth and issuing in temporary springs, while water remains twice as long in the fractured bedrock itself. The different residence times have a marked influence on the water quality, with the perennial springs supplying water of superior quality. Hence, these springs are used to supply drinking water to the villages, while the temporary springs are used for irrigation purposes only.

The water recovered from the springs is only a fraction of the recharged water. A large portion is used up by maintaining high soil moisture contents down slope of the irrigation channels. This had a lasting effect on the area, as dense vegetation has been established. The system requires no sophisticated infrastructure and is believed to be applicable to other hard rock areas around the world.

REFERENCE: Pulido-Bosch, 1995. Centuries of Artificial Recharge on the southern edge of the Sierra Nevada. Environmental Geology. v.26. pp. 57-63.

I. ENHANCEMENT OF GROUNDWATER RECHARGE IN HUNGARY BY BANK FILTRATION FOR DRINKING WATER SUPPLY

Bank filtered water meets one third of public water demand, and is of crucial importance for drinking water supply in Hungary. The drinking water supply of Budapest entirely relies on the bank-filtered water of the Danube. The abstracted amount is only limited by the filtration capacity of the bank; the discharge of the river is an order of magnitude greater than the abstracted amount. Practically there will be no limitation from the resource side, which gives this resource 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 of the water. The natural filtration capacities of the exploited river sections are very efficient, no micro-pollutants have been found in the abstracted water. This advantage is valuable for users requiring high quality drinking water for public supply and some industrial use, but not for irrigation. Well fields exploiting bank-filtered water are mostly along the Danube, only two can be found on other rivers (one in the south-western part of the country, and one in the northern part). The actual use is 0.9 Mm^3/day (75% for public purposes), the further potential capacity is approximately 4 Mm^3/d, out of that 300 000 m^3/d capacity is protected as designated future water resources.

REFERENCE: Simonffy, Z. 2003. From Chapter 5 of "Management of Aquifer Recharge and Subsurface Storage." NCC-IAH Publication. No. 4.

J. AQUIFER RECHARGE THROUGH WELL INJECTION IN MEXICO

Because more than a half of its territory is dominated by arid and semi-arid climatic conditions, groundwater constitutes an essential resource for development in Mexico. Total groundwater abstraction has been estimated at of 28000 Mm^3/a. Agriculture uses 71% of that volume, whereas urban and industrial areas consume 26%. The urban population constitutes 65% of the total inhabitants in Mexico (100 million). For example, 21 million people live in the Metropolitan Area of Mexico City. Mexican cities consume 7600 Mm^3/a and groundwater constitutes two thirds of that supply. More than 100 regional aquifers are over-exploited with a yearly abstraction of 5400 Mm^3/a from storage and the resulting environmental consequences during the last four decades.

A pilot aquifer recharge project was carried out in the Comarca Lagunera Region of northern Mexico, which 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. At present, it is estimated that abstraction is at least three times greater than the recharge, resulting in a significant decline in the piezometric surface and deterioration in groundwater quality. The main concern is the occurrence of arsenic in groundwater at concentrations well above the WHO guideline value for domestic use of 0.05 mg/L, now reduced to 0.01 mg/L.

The pilot scheme used an adapted recharge sand basin near to the Nazas River Bed, in Torreon City, covering an area of 13 ha with a storage capacity of about 197,000 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 and twelve pre-existing wells were conditioned for additional water table monitoring. During the trial between May and August 2000 a total volume of 5.2 Mm^3 was conveyed through Sacramento channel to the recharge basin. Of this volume, 0.2 Mm^3 was evaporated and 5.0 Mm^3 infiltrated to the subsurface. Water infiltration capacity was reduced from 2.4 m/d to 0.116 m/d due to clogging.

Recommendations from the pilot scheme included building new structures to control delivery of water to the basins, to release up to 0.5 Mm^3/week to avoid basin spills, to construct parallel sedimentation basins to reduce clogging and to construct adsorbtion wells 20 m deep and >0.3 m in diameter to avoid low conductivity horizons.

REFERENCE: Chavez-Guillen, R. 2003. From Chapter 6 of "Management of Aquifer Recharge and Subsurface Storage." NCC-IAH Publication. No. 4.

SELECTED KEY REFERENCES

Only selected key references are given here. Other references can be found in the searchable database at www.iah.org/recharge

Artificial Groundwater Recharge, 1983. Huisman, L and Olsthoorn, T N. Pitman, Boston ISBN 0-273-08544-01.

Artificial Recharge of Groundwater, II: 1994. Proceedings of the Second International Symposium on Artificial Recharge of Ground Water, July 17-22, 1994, Orlando, FL, United States, American Society of Civil Engineers, New York, NY, United States,

Artificial Recharge of Groundwater 1996. Proceedings of an International Symposium, Helsinki, Finalnd, Nordic Hydrologic Programme Report #38.

Artificial Recharge of Groundwater, III: 1998. Proceedings of the Third International Symposium on Artificial Recharge of Ground Water, Amsterdam, Ed Jos H Peters, Balkema.

Management of Aquifer Recharge for Sustainability: 2002. Proceedings of the Fourth International Symposium on Artificial Recharge of Groundwater (ISAR-4), Adelaide, Australia. Ed. P. J. Dillon. A. A. Balkema.

Artificial recharge of groundwater: hydrogeology and engineering. 2002. Bouwer, H in Hydrogeology Journal 10:121-142.

Atelier Sous-Regional sur la Collecte des Eaux de Surface en Afrique de L' Ouest et du Centre, tenu à Niamey au Niger du 26-29 Octobre 1999 – FAO RAF, Case studies: Nigeria, Cameroon, Burkina Faso, Niger, Mauritanie, Gambie and Tchad.

Groundwater and Society: Resources, Tensions and Opportunities. 2000. Burke, J J & Moench, M H. Themes in groundwater management for the 21st century. United Nations Publication.

Groundwater recharge and wells – A guide to Aquifer Storage and Recovery. Pyne R. D. G. 1995. Lewis Publishing, Florida, USA. Second Edition 2005.

Guide on Artificial Recharge to Ground Water. 2000. Central Ground Water Board, Govt. of India. New Delhi.

Guidelines on the Quality of Storm water and Treated Wastewater for Injection into Aquifers for Storage and Reuse. Dillon, P and Pavelic, P. 1996 Urban Water Research Association of Australia Research Report No. 109.

Rainwater harvesting and Artificial Recharge to Groundwater: a guide to follow. 2000. UNESCO-IHP and Central Ground Water Board, Govt. of India, New Delhi.

Standard Guidelines for Artificial Recharge of Groundwater. 2001. Environmental and Water Resources Institute, American Society of Civil Engineers, 2001. EWRI/ASCE 34-01.

Water Harvesting, A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. Critchley, W, Siegert, K, Chapman, C and Finkel, M. FAO publication AGL/MSC/17/91. Available on line at: http://www.fao.org/docrep/U3160E/U3160E00.htm. Also, training workshop on water harvesting available in 2002 on CDROM in English, French, Spanish, Arabic and Chinese: http://www.fao.org/ag/AGL/aglw/wharv.htm

Management of Aquifer Recharge and Subsurface Storage. 2003. NCC-IAH Publication. No. 4.

Management of Aquifer Recharge and Water Harvesting in Arid and Semi-arid Regions of Asia. 2005. Proceedings of a UNESCO sponsored workshop in Yazd, Iran. November 2004.

Health Risks in Aquifer Recharge Using Reclaimed Water. 2003. Aertgeerts, R and Angelakis, A. (Eds.) SDE/WSH/03.08. World Health Organization.