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The effectiveness of Artificial Recharge of groundwater: a review

Groundwater Systems and Water Quality Programme

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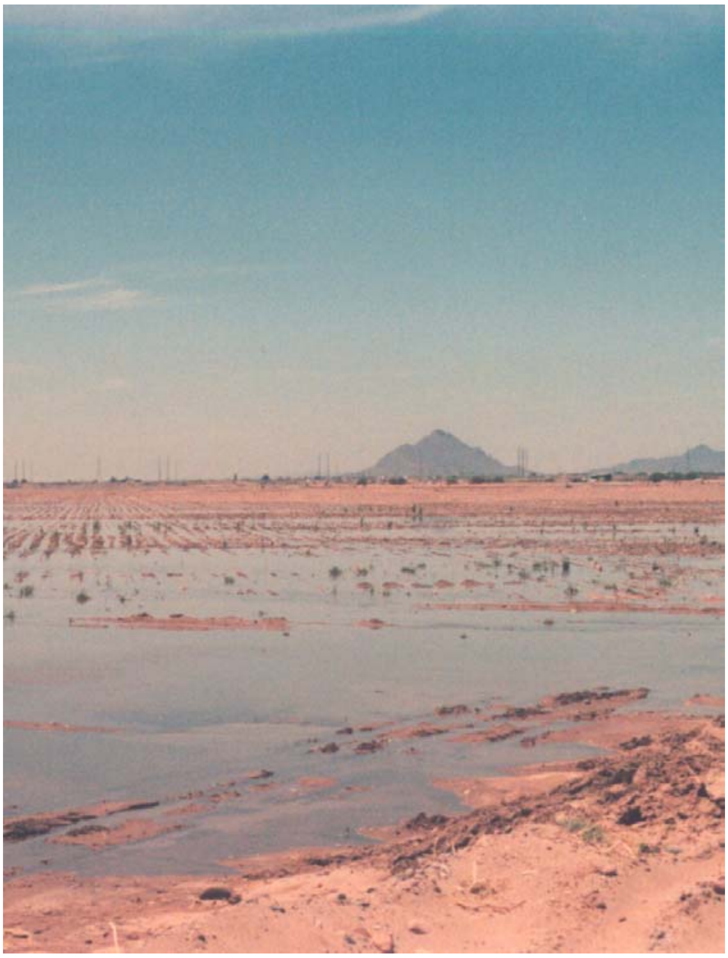

BRITISH GEOLOGICAL SURVEY

COMMERCIAL REPORT CR/02/108N

The effectiveness of Artificial Recharge of groundwater: a review

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Spreading basin near Phoenix, Arizona, USA

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Summary

This report is the principal technical output of a project commissioned by the Department for International Development to review the current state of knowledge regarding the effectiveness of Augmenting Groundwater Resources by Artificial Recharge (AGRAR). The focus of this study is on applications to rural environments and communities in semi-arid developing countries but does also refer to applicable users in urban situations.

Water harvesting and, to a lesser extent, artificial recharge are currently being promoted as solutions to water scarcity in many nations, especially India. Artificial recharge is one of many techniques used to manage water resources and its efficacy may be limited by a combination of technical and socio-economic factors.

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

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

Rainwater harvesting and artificial recharge contribute to the maintenance of the above benefits, particularly if practised as part of a wider approach to water resource management that addresses demand and quality dimensions as well as supply aspects.

Numerous schemes exist to artificially recharge groundwater and they are as varied as the ingenuity of those involved in their construction and operation. Broadly, they can be grouped into the following categories:

- Spreading methods
- Open wells and shafts
- Drilled wells and boreholes
- Bank infiltration
- Sand storage dams
- Roof-top rainwater harvesting,

The effectiveness of artificial recharge schemes is governed by climate, geology and hydrogeology, topography, source water availability and quality, operational and management issues, regulatory controls and environmental and socio-economic considerations. The complex interaction of some or all of these factors will determine the degree of success, which itself can be viewed from a variety of perspectives. Broadly, however, the factors can be categorised into physical/technical and socio-economic issues.

- Physical technical conditions determine the to effectiveness of artificial recharge schemes:
    - Soil type (infiltration capacity and distribution)

  - o Source of water (rivers, rainfall distribution/intensity, wastewater etc.)
  - o Sub-surface storage capacity (geology, degree of confinement, permeability, groundwater flow and quality etc.)
  - o Artificial recharge method applied (spreading, well, boreholes etc)
  - o Management and maintance scheme (government, NGO, community).
- Socio-economic conditions, including:
  - o The demand for additional groundwater from either man or the environment
  - o The economics of artificial recharge
  - o The incentives communities may have for implementing and maintaining artificial recharge activities;
  - o Whether or not artificial recharge is likely to be implemented as part of a wider package of management interventions

In the context of sustainable groundwater management, it is essential to assess the effectiveness of artificial recharge schemes in terms of their ability to recharge the aquifer. However, effectiveness can be difficult to measure directly. A detailed water balance study provides a quantitative estimate of the contribution of a scheme to groundwater recharge. However, these are very expensive and require technical expertise. Existing methods should be developed into indicative measures of the effectiveness of artificial recharge and these methods need to be applied widely to promote improved management of schemes.

The uncertainties associated with artificial recharge need to be addressed through systematic assessments of the water balances of artificial recharge schemes in a variety of environments in order to provide guidelines on their effectiveness and sustainability. The importance of different management strategies also needs to be assessed in relation to their impact on livelihoods. Bringing these aspects together will provide sound data and guidelines for future investment and sustainable implementation.

The sets of criteria devised for the effective implementation and management of individual schemes, as well as at watershed and regional scales, need to be developed collaboratively with implementers, founders and policy makers. Guidance materials produced will need to be tailored to the needs of end users and their full involvement is needed to ensure knowledge is effectively and appropriately disseminated and internalised.

Artificial recharge should be used in conjunction with other sources of water (rivers, lakes, groundwater etc.), and a range of other water management methods including, demand management, conjunctive use, storm water and waste water reuse etc. Only through an improved understanding of the technical effectiveness of recharge structures, combined with a clear assessment of the social and economic benefits and constraints, as well as the impacts on livelihoods, will management of artificial recharge improve.

1 Introduction and objectives of the project

Groundwater is the main source for rural water supplies in many semi-arid developing countries. Over recent years, increasing abstraction to meet rising demand for domestic supplies and irrigation has raised concerns for the sustainability of the resource and the livelihoods it supports. Additionally changing land use as well as hydrological interventions and climate change will have impacts natural recharge and groundwater storage. Consequences of over-exploitation include declining water levels and increasing competition for scarce water resources between domestic and agricultural users and rural and urban communities.

To address these concerns, considerable emphasis is being given to the augmentation of natural recharge by both traditional and modern techniques. Some of these techniques have been employed for centuries, ranging from simple check bunds in gullies to complex diversion and infiltration structures as well as injection wells. Recently there has been considerable investment and renewed effort to restore and maintain such traditional facilities as well as building new structures. Much of the current effort is, however, empirical in choice of sites, structures and aquifers. Performance monitoring is rudimentary and benefits often anecdotal. Because there has been no systematic evaluation of their technical and economic performance, or their impacts on livelihoods, the overall benefits of recharge augmentation schemes may currently be over-emphasised. If the management of the demand side of the water balance (groundwater abstraction) is not also addressed, the benefits of recharge augmentation may not be significant and groundwater resources may continue to be over-exploited.

Many artificial recharge schemes have been implimented to augment groundwater resources around the world. This experience has been reported at national and international conferences as well as in other disparate reports, often not widely available. The technical, societal, economic and environmental impacts of these schemes are seldom evaluated in detail and thus their effectiveness is often difficult to quantify.

The aim of this project is to review experience from around the world, from existing artificial recharge sites and reports, and to produce a critical assessment of methodologies and the effectiveness of schemes. The main focus will be on experience with low technology methods in rural India, where there are many hundreds of thousands of schemes, but will also draw on wider experience applicable to AR in arid and semi-arid areas. The outputs will aim to provide an introduction to AR, access to further information and a network of proctxxx and facilitate governments, donors and NGOs to make informed decisions on the role of artificial recharge in rural water supply and groundwater management projects/programmes.

The approach taken was to:

- develop a web site and a network of researchers and practitioners in conjunction with the International Association of Hydro geologists (IAH) Working Group on Managing Aquifer Recharge – IAH-MAR. www.iah.org.recharge;
- use the web site to (i) disseminate the results of the interdisciplinary review of artificial recharge, (ii) maintain databases of references, researchers and artificial recharge schemes, and (iii) provide a forum for discussion;
- review experience from around the world, from existing artificial recharge sites and reports, and produce a critical assessment of methodologies and the effectiveness of schemes;

- discuss the results of the review of artificial recharge with collaborating organisations and;
- make recommendations for a programme of further collaborative research to address issues raised.

This report comprises the results of the review undertaken between April 2001 and March 2002. In addition to an extensive literature search, two visits were made to India to meet a wide range of practitioners and to visit artificial recharge schemes. The second visit in November 2001 included a seminar at which the state of knowledge of artificial recharge was discussed together with issues that need to be addressed in order to provide improved guidelines for the effective implementation and management of schemes. These issues form the basis for the proposed Phase 2 of the project in which sites will be monitored, data relating to the physical and impacts on livelihoods collected and analysed and recommendations made and disseminated.

The authors are therefore indebted to the contributions made by the collaborating organisations and individuals, including;

- Institute for Social and Environmental Transition (ISET), Nepal & USA. (Dr M Moench) Co-author
- Vikram Sarabhai Centre for Development Interaction (VIKSAT), Gujarat. (DR S Mudrakartha)
- Institute of Development Studies (IDS-Jaipur), India. (Prof M S Rathore)
- Central Groundwater Board (CGWB), Govt. of India. (Dr D K Chadha)
- Department of Drinking Water Supplies (DDWS), Ministry of Rural Development. (Dr N Kittu)
- Nepal Water Conservation Foundation (NWCF), Nepal. (Dr A Dixit)
- Tarun Bharat Sangh (TBS), Rajasthan. (Mr R Singh)
- Advanced Centre for Water Resources Development and Management (ACWADAM) Pune. (Dr. H Kulkarni)
- Tamil Nadu Agricultural University (TNAU) Coimbatore. (Dr K Palanisami)
- National Geophysical Research Institute (NGRI), Hyderabad. (Dr M Thangarajan)
- Bhabha Atomic Research Institute (BARC) Trombay. (Dr S V Navada)
- UNICEF, India Office. (Mr Rupert Talbot and Mr V Joshi)
- UNESCO New Delhi Office. (Dr R Jaykumar) and Paris Office (A Aureli)

In addition, Mr David Macdonald (BGS) has provided valuable input as part of the project team and has, together with John Chilton, peer reviewed this report.

The report firstly introduces the project and the context in which it was undertaken (this Chapter), followed by descriptions of various artificial recharge methodologies used to meet a wide range of demands in a variety of physical settings (Chapter 2). The impacts of different physical factors on the effectiveness of schemes are then discussed (Chapter 3), followed by a discussion of the socio-economic factors and their impacts on livelihoods (Chapter 4). The overall benefits, constraints and uncertainties are drawn together in Chapter 5.

2 Artificial recharge methodologies

2.1 WHAT IS ARTIFICIAL RECHARGE?

Artificial recharge is defined here as the augmentation of groundwater resources, brought about as a result of man's activities. It is carried out all over the world 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, especially with respect to agriculture. This practice is also known as rainwater harvesting and has been practiced for thousands of years in arid and semi-arid areas. In India, tens of thousand of xxxx of field xxx have been constructed to prevent runoff and soil erosion as well as increase percolation. Related to drinking water supply, the principal reason is to provide a sustainable resource as well as enhancing the water quality by soil-aquifer treatment (SAT). Other reasons to recharge water artificially include the control of saltwater ingress, the augmentation of low river flows, reducing runoff and soil erosion absorption of floodwaters to reduce their destructive capacity and the control of subsidence.

Artificial recharge not only provides an effective means of storing water enabling better management of available resources it can also impact on the water quality resulting in a beneficial manner. Quality changes results from physical removal of particle matter, microbiological removal of pathogens and organic material, dilution or displacement of poor quality ground water and geochemical integration with the notive groundwater and the aquifer material. Soil Aquifer Treatment (SAT) is a technique developed specifically to improve the quality of water (Bouwer, 2002) by managing chemical and microbiologic processes during infiltration in speeding boring. The recharge water is then mainly used for irrigation of fodder crops as well as municipal irrigation. Bank filtration (Germany) and dune filtration (The Netherlands) are techniques that have been used for decades to treat and store poor quality river water by redirecting it to flow through natural sediments in order to remove suspended solids, pathogens and some organic and chemical components. Understanding the processes involved has enabled effective management of the schemes to maximise the beneficial impacts and maximise the detrimental areas e.g. increased iron content, reduced dissolved oxygen. Although the benefits of suspended soils and the active "bio reactions" associated with spreading schemes are lost with direct injection into confined aquifers, there are still beneficial impacts on waster quality associated with these schemes. Although the removal of nitrate and other agencies has clear benefits to improving the quality of waster injected into Aquifer Stargo Recover (ASR) schemes, the red ox reactions associated with injecting aerobic recharge water into an aerobic aquifer for storage need to be understood and managed in order to avoid clogging or the recovery of water with unacceptable quality. In sight into understanding and managing water quality impacts can be found in Pyre, 1995 and Dillon (el), 2002.

Artificial recharge is one of many techniques used to manage water resources and should be regarded as one method to be used in conjunction with a wide range of others, including surface storage, exploitation of groundwater, demand management, waste water reuse etc. Artificial recharge is currently being promoted as a significant solution to water scarcity in many nations, especially in India.

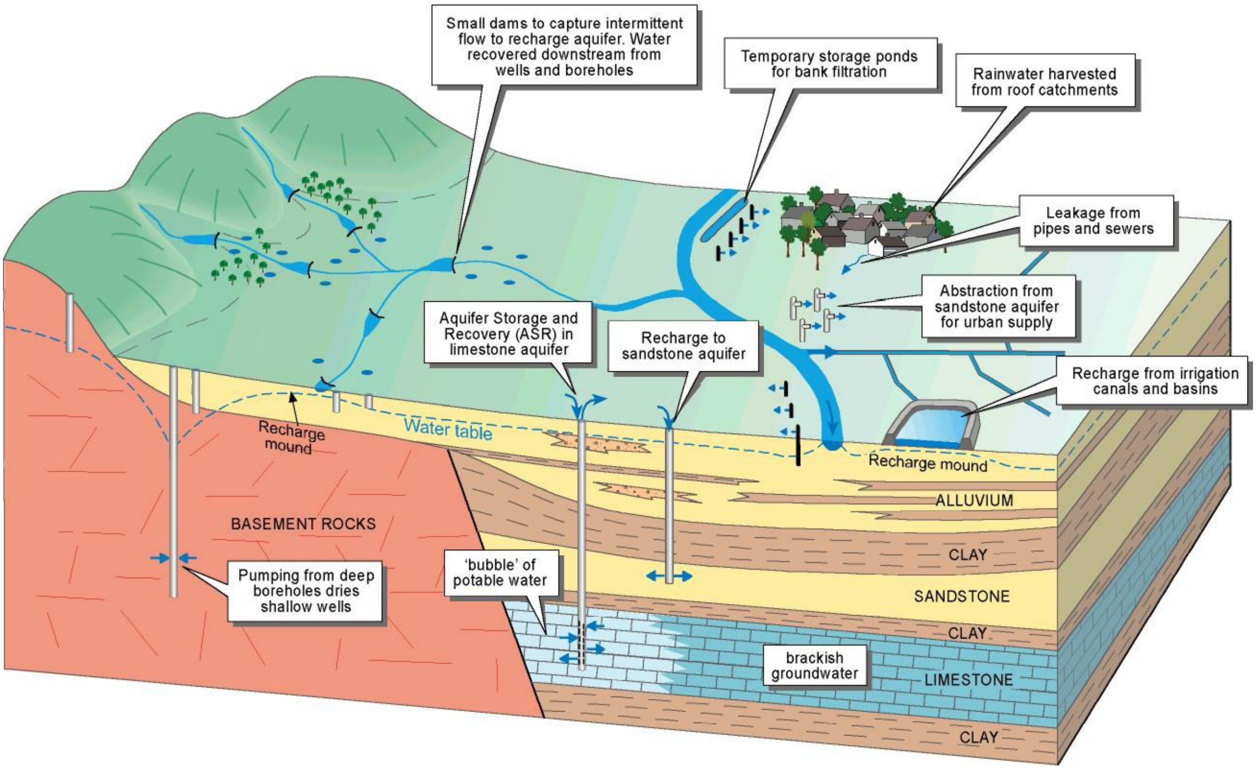

Figure 1 Diagram of different artificial recharge methods in different hydro geological environment

Numerous schemes exist to artificially recharge groundwater and they are as varied as the ingenuity of those involved in their construction and operation. Broadly, they can be grouped into the following categories:

- spreading methods,
- open wells and shafts,
- drilled wells and boreholes
- bank infiltration,
- sand storage dams
- roof-top rainwater harvesting,

all of which will be described briefly below and shown in Figure 1. Many schemes require low levels of technology and can be (and have been for centuries) implements with little engineering knowledge. This would include water harvesting techniques to enhance recharge, field boring and small bunds across ephemeral streams. Well digging skills have been developed over the years and diversion of flow into these (despite the problems described in 2.3) subsequent to settlement of most suspended solids, is becoming increasingly popular in Gujarot, India. Sand storage dams, spillways to river bank, and perennial dams require more engineering design and knowledge, increasing further when using drilled wells and boreholes for injection or for Aquifer Storage Recovery (ASR). Although simple in principle the efficient operation of spreading basins and baulk infiltration schemes needs a good knowledge of the physical, hydraulic, geochemical and microbiological processes in operation and how to mange them for optimum performance. Similar issues need to be addressed in roof top rainwater harvesting. For further details on the nature of these schemes, e.g. construction, restoration etc. the reader is referred to (Central Ground Water Board, 2000) , (CGWB/UNESCO, 2000) (National Institute of

Hydrology, 1998) (American Society of Civil Engineers, 2001), (O'Hare et al., 1982), (Huisman and Olsthoorn, 1983), (Pacey and Cullis, 1986) and (United Nations, 1975).

2.2 SPREADING METHODS

Water spreading is applied in cases where the 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 for the scenarios described.

However, 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 maintain infiltration rates and keep evaporation from open water to a minimum. Few estimates have been found of the proportion of the water that evaporates from these structures in these situations and this is an area where additional data collection could benefit management strategies greatly.

A study in Karnataka, India (Batchelor et al., 2000) measured the annual water balance in an irrigation tank that is considered to function solely as surface water storage and does not contribute to groundwater recharge. This study gives useful estimates of evaporative losses from open water, which is a feature of spreading methods of Artificial Recharge. Crystalline basement rocks underlie the area and the climate is semi-arid to arid; the average rainfall ranging from 470 to 570 mm. In the period June 1989 to May 1990 (a period of average rainfall) the components of the water balance were calculated to be: storage 23%; withdrawal for use, 32%; evaporation, 34% and outflow, 11%. In the prevailing climatic conditions, loss to evaporation from open water is about 2000 mm/a; equivalent to an average daily rate of 5.5 mm/day. The high proportion of loss to evaporation can be greatly reduced if the water is stored underground through artificial recharge. This is discussed further in Section 3.2.

2.2.1 Infiltration or Recharge Basins

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

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. On the other hand, depths should be large enough to prevent deep penetration of sunlight, which would result in rooted aquatic growth and consequent resistance to the lateral flow of water. Large areas of land have to be made available for infiltration basins and the method delivers a relatively low recharge rate per unit area utilised (O'Hare et al., 1982).

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:

- raise the water level in the basin to increase in driving head.
- apply a rotational system of water spreading and drying and subsequent scraping of the basin. Drying kills microbial growth, and this, combined with scraping of the basin bottom, reopens soil pores.
- 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 prevent 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.

2.2.2 Perennial dams

Semi-perennial or perennial dams gather larger quantities and depths of water, which can be used both as a source of water for direct irrigation as well as for increasing groundwater recharge. Silting over successive periods of inflow will lead to a reduction in the effectiveness of the recharge structure. The hydraulic head resulting from the accumulation of several meters of water will also force fines further into the infiltration surface and will compact the sediments, further reducing their effectiveness. Evaporation will be at the full potential open-water rate but estimates of the significance of this loss are not easily come by. All these factors should be appreciated and, if possible, quantified to ensure that the dams are managed as either recharge or storage structures. A good understanding the hydraulic performance of structures will enable clarification of differing stakeholder expectations.

Plate 1 Construction of an earth dam by a community of farmers in the Alwar district, Rajasthan, India.

2.2.3 Ditch and Furrow

These facilities consist of a series of ditches or furrows that are flat-bottomed and closely spaced to obtain maximum water contact area. Different layouts do exist, but commonly a main canal successively branches into smaller canals and ditches, with a collecting ditch at the very end of the site to convey excess water back into the main channel. Gradients of the major feeder ditch should be sufficient to carry suspended material through the system to prevent rapid clogging of the facility.

Clogging is the main cause for declining recharge rates in this type of facility. Methods to counteract this process are similar to those described in the section on recharge basins.

2.2.4 Flooding

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.

2.2.5 Irrigation

Irrigation schemes are frequently a major source of unintentional recharge to aquifers. For example in arid and semi-arid areas where deep percolation is relied upon to leach salts out of the root zone, the intention is not to recharge the aquifers. The net outcome may be recharge with poor quality water leaking to main groundwater levels and water logging. Water can also be spread deliberately during dormant or non-irrigating seasons specifically propose of for the AR. As a distribution system is already in place, no additional cost for land preparation is needed. Irrigation is, however, often carried out on flat plains where the water table is at shallow depths. This implies little volume available for storage of water and it is frequently the case that measures have to be taken to avoid waterlogging, through drainage ditches and channels. Even where the groundwater levels were originally found at considerable depth, deep percolation of water applied to leach salts from the root zone, can result in water tables rising to shallow depth, require control and management. The quality of water under irrigated areas also needs to be assessed carefully as it can contain unacceptable concentrations of leached salt as well as residual agricultural chemicals and leaching from the soil zone.

2.2.6 Stream channel modification

An inexpensive way of spreading water can be achieved by the construction of bunds across a streambed with the construction material being *in situ* river alluvium. (Plate 1) To avoid annual erosion or destruction of theses structures a concrete spillway is often constructed (Plate 2) and to certain and channel surface runoff, extensive field bunds are also built. The bunds retard the water flow in the stream and thus create an opportunity for this water to infiltrate into the ground.

Plate 2 Typical spillway structure on a bundied field, Alwar District, Rajasthan, India.

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 of sediment transport and hence erosion. As the water is only bounded 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 India, some of these structures are referred to as 'infiltration tanks' as impounding walls or bunds are needed beyond the main dam/spillway structure. The land surface in the tanks tends not to be used for agriculture when it dries out and, in consequence, the infiltrating surface needs to be renovated to maintain infiltration rates. The silt removed is used to maintain the structure or distributed onto adjacent agricultural land.

Open water evaporation from these structures can be a significant loss and can vary greatly, depending on the nature of the medium through which infiltration occurs. The results of only a few quantitative studies have been found and these are described in Section 3.2.2.

2.3 OPEN WELLS AND SHAFTS

These structures are used to recharge shallow pyretic aquifers and are often wells that have run dry. The walls of structures may need to be supported to avoid collapse in unconsolidated sediments. Pre-settlement of 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. The significance of the contribution made by this method needs to be compared to the quantity of recharge occurring naturally, but it could be valuable where shallow, low-permeability layers constrain infiltration from the surface.

Plate 3 Large hand-dug pit used to recharge fractured hard-rock aquifer using occasional flash-flow off surrounding fields, Rajasthan, India.

This method 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, that of the water infiltrating from the surface passes through soil and alluvial deposits which can act as extremely effective filter/treatment mechanisms.

Pits and trenches may suffer from decreasing recharge rates due to accumulation of fine-grained material. Pit bottoms are mainly affected, while the steep sidewalls remain relatively unclogged (Murray and Tredoux, 1998). If coarse material is used to fill pits or trenches, it has to be replaced if clogging becomes severe. Other methods employed to maintain infiltration rates are mentioned earlier in the section describing infiltration or recharge basins.

In loosely consolidated material, recharge pits and trenches are used in cases where low permeability material overlies the aquifer, which occurs at trench able 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 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.

2.4 DRILLED WELLS AND BOREHOLES

Well or borehole recharge is used where low permeability strata overlie target aquifers, in order to recharge water directly into the aquifer. This technique is suitable for deep-seated aquifers and has the advantage that the recharge water can bypass thick impervious layers to be introduced to the most permeable portions of the aquifer (Murray and Tredoux, 1998). Recharge wells are also advantageous when land is scarce (O'Hare et al., 1982). 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 manual, but can be found in (Pyne, 1995). Where the well/borehole is used for both injection and recovery (Aquifer Storage and Recovery: ASR), costs are minimised and clogging is removed during the recovery cycle.

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. Boreholes are also used, particularly for deeper confined aquifers. Clogging and contamination are particular concerns and pre-treatment of the water is essential. Performance is often best maintained when the boreholes are used for both recharge and recovery of water, as the recovery phase tends to back-flush the system.

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 plain sedimentation or filtration to remove suspended solids. Settling efficiency can be increased by addition of flocculating chemicals. Additionally, the water should not be allowed to cascade into the borehole, as this will entrain air that will clog the aquifer. 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.

2.5 BANK INFILTRATION

Riverbed infiltration schemes commonly consist of a gallery or a line of wells 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 a 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 enhanced infiltration schemes are a dependable source of surface water of acceptable quality, 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 considerably 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. To prevent a rapid clogging of the stream bed or lake bottom,

- the rate at which the surface water enters the aquifer must be low;
- the riverbanks and beds should be scraped during periods of low flow in order to remove accumulated silt, clay or organic matter.

2.6 SAND STORAGE DAMS

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 artificial 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 a coarse sandy sediment (e.g. granites, sandstones, quartzite’s) to make up the artificial aquifer material. With time, successive floods built 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.

Settling of fine material and subsequent clogging of the artificial aquifer is the main problem encountered in sand dams (Murray and Tredoux, 1998). The situation can be improved by:

- Openings in the dam wall 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.
- siltation ponds may be constructed upstream of the facility to allow fine particles to settle out before the recharge water is applied to the dam.

2.7 ROOF-TOP RAINWATER HARVESTING

Rooftop rainwater harvesting can conserve rainwater for either direct consumption or for recharge of groundwater. This approach requires connecting the outlet pipe from a guttered rooftop 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, aluminium, galvanised iron or fibreglass, in order to avoid contaminating the rainwater.

Where the water is used for direct consumption, the initial water from a rain shower 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. If the water is to be used for drinking purposes, filtration and chlorination or disinfection by other means e.g. boiling, is necessary (Pacey and Cullis, 1986).

Advantages of collecting and storing rainwater in urban areas is the reduction of demand on water supply systems as well as reducing the amount of storm-water run-off and consequent urban flooding.

2.8 COST EFFECTIVENESS

The benefits of storing water by Artificial Recharge can extend well beyond a simple quantification of the cost of constructing and maintaining a structure or scheme compared to the volume of water that is recoverable. This is one measure but the benefits of having a sustainable water resource may permit self-sufficiency in food production, permit income generation, free-up time previously used to collect water from distant sources etc. These issues are discussed din greater detail in Sections 4 and 5. Comprehensive analyses of all the factors involved are not widely available, in particular at the low-technology end of the spectrum.

An attempt to quantify the benefits of a variety of water harvesting schemes in India was made by the Central Ground Water Board (CGWB, 2000). A cost-benefit analysis of a scheme in the Amravati District, Maharashtra looked at 3 Percolation Tanks and 10 cement plugs in gullies. For the tanks, the additional area brought under cultivation was about 60 ha, and the assumed income generated over a 25-year period of 10 000 Rs/ha/yr (£154). The total costs of construction of the three tanks of 76,98,240 Rs (£118,400) together with annual maintenance is calculated to be 3,38,721 Rs/yr (£5,200) compared with an annual income due to the assured irrigation of 5,96,800 Rs/yr (£9,180); a ratio of 1:1.75. A similar analysis of the ten schemes impounded by cement plugs (average cost of construction 93,200 Rs-£1,400) gives a cost/benefit ratio of 1:1.9.

A similar exercise was undertaken in the Jalgaon District, also in Maharasthra, (CGWB, 2000) where six Percolation Tanks have an average calculated cost/benefit ratio of 1:6.8. The much higher ratio is related to the much cheaper construction costs at this site, averaging 3,92,500 Rs (£6,000) compared to 25,66,000 Rs (£39,000) at the Amravati District site. Some of the savings were due to conversion of existing structures from irrigation tanks to percolation tanks. The same analysis was applied to an injection well; two recharge shafts and a dug well recharge structure in the same district. Cost/benefit ratios ranged from 1:0.7 to 1:17.8, again illustrating that on this measure alone, high construction costs are difficult to recoup over the expected life of a structure and that careful assessment of the cost/benefit ratio is needed prior to initiation of a project.

2.9 CONCLUSIONS

The level of sophistication of the technology required to practise Artificial Recharge depends largely on the hydro geological situation where it is to be applied, the need for additional water storage as well as the availability and quality of source water. Spreading techniques can be applied in a wide variety of forms where the surface (or near surface) layer is permeable. These techniques can be simple and low cost both in construction and maintenance. However their effectiveness is seldom quantified; the benefits accrued from the capital outlay and effort required for construction and maintenance being reflected in anecdotal evidence of higher water tables, longer base flow in streams and longer periods when wells do not dry. A measure often used is the additional area that can be irrigated but this is not put into the context of the overall balance of water resources and sustainability.

Where surface layers are impermeable but water can potentially to be stored in underlying aquifers then wells or boreholes are required to access these aquifers. Here more sophisticated technology is required and better control on the suspended solids load and quality of the source water is required. This is usually reflected in the amount of data that are collected but also in the scale of projects, which are orders of magnitude smaller than those using spreading techniques. The greatest potential for well recharge seems to be in urban situations where roof-top rainwater harvesting can be used as a source of recharge water or aquifers can be used as temporal stores of potable water (Aquifer Storage and Recovery) as part of water supply management schemes.

Simple cost/benefit analysis can be indicative of the period expected to recoup the investment. However other impacts and benefits, seldom quantified, are not included in these calculations.

3 Physical environment factors determining the effectiveness of Artificial Recharge

3.1 INTRODUCTION

The effectiveness of artificial recharge schemes is governed by climate, geology and hydrogeology, local topography, source water availability and quality, operational and management issues, regulatory controls and environmental and socio-economic considerations. The complex interaction of some or all of these factors will determine the degree of success, which itself can be viewed from a variety of perspectives. Broadly, however, the factors can be categorised into technical (this chapter) and socio-economic issues (Chapter 4).

A detailed description of technical issues affecting the effectiveness of artificial recharge schemes is given below. An attempt to clarify and simplify these issues through tabulation is shown in Table 1, where parameters considered to be significant are described in respect to a broad hydro geological classification. At the end of this chapter various methodologies to measure the effectiveness of artificial recharge structures to replenish the aquifer are introduced and discussed.

3.2 CLIMATIC AND HYDROLOGICAL CRITERIA

3.2.1 Introduction

Precipitation has to meet the demands of evaporation, evapotranspiration and where the soil-moisture deficit has been met or the infiltration rate has been exceeded, surface runoff. Water that infiltrates to the water table provides natural recharge to aquifers and this varies greatly in quantity and timing, depending on climate and other hydrological factors. In temperate humid climates natural recharge is typically 30-50% of precipitation; reducing to 10-20% of precipitation in Mediterranean climates and about 0-2% in dry climates (Bouwer, 2002 and references therein).

Climatic and hydrological conditions influence the applicability of artificial recharge methods, as they will determine the quantities of water that will be available for storage. Under humid conditions precipitation is often sufficient to replenish groundwater while satisfying the needs of evaporation and still providing a base flow component to streams. However, seasonal mismatch between supply and demand, e.g. peak summer demand, can call for artificial recharge to be considered to alleviate these water supply and storage problems. Under these conditions groundwater can be recharged in the wet or winter season for use during periods of higher demand.

In semi-arid and arid areas the annual potential evaporation is often considerably higher than the average annual precipitation. However, when precipitation occurs, it is often in form of short and heavy rainstorms (monsoon climate). During these periods, precipitation exceeds the potential evaporation and soil moisture is replenished. In extreme events the infiltration capacity is also exceeded and surface run-off and flooding can occur. Natural recharge does occur to some extent, although increasing aridity is characterised by decreasing groundwater replenishment and greater time variability between recharge events.

River flow under semi-arid or arid conditions is perennial only if surface watercourses are fed by groundwater or from a distant source beyond the climatic region (e.g. glacier melt water). In arid areas, ephemeral rivers are common, and flow only occurs in response to storms. Under these conditions, consideration has to be given to the availability of recharge water. Depending on the aridity of the area, surface water may not be available in sufficient quantities for recharge. Source water may be restricted to flash floods or water from desalination plants.

In humid, tropical areas, precipitation generally exceeds the potential evaporation, in spite of the hot climate. However, very intense storm events often alternate with dry seasons, in which a temporary deficit of water occurs and artificial recharge of groundwater should again be considered as a cost-effective method of storing water.

In general, the flow characteristics of the stream providing the source water at the proposed artificial recharge site should be determined, to evaluate the average and seasonal flow availability. The volume, together with the spatial and temporal variability of the source water has to be estimated. This is a straightforward calculation if the source is a permanent stream with a relatively long record of flow. If the water is taken from ephemeral streams or other intermittent sources like storm sewers, the determination of the available volume has to take its temporal distribution into account. In these cases rainfall-runoff models might be applied to aid in arriving at an estimate (O'Hare et al., 1982).

3.2.2 Water balance

The assessment of the effectiveness of an artificial recharge scheme, or group of schemes, can be approached in many ways, as discussed in Section 3.6. However, an overall understanding is best gained from a quantification of the components of a water balance, broadly – precipitation, evaporation, surface flow and change in groundwater storage. These components need to be viewed not only on an average annual basis but also in time and space. For example, in an area where the annual evaporation greatly exceeds the annual precipitation, availability of water for natural or artificial recharge may not appear to be available. However, if localised precipitation occurs for brief periods, the infiltration capacity may be exceeded and surface flash flow may occur. Structures to harvest this flow, through artificial recharge, and at the same time reduce soil erosion are common in arid and semi-arid regions.

An example of a water balance study is the Karnataka Watershed Development Project (Batchelor et al., 2000). This study looked at three watersheds with areas of about 12000 to 18800 ha; two underlain by crystalline basement complex and one by Basaltic Deccan Trap geology. The climate is semi-arid to arid and annual average rainfall ranges from 470 to 570 mm. During an average year the natural recharge of groundwater amounts to only 6-8% of rainfall in the watersheds underlain by basement complex and about 20% where underlain by basalt trap geology. Runoff from the watersheds is estimated to be between 2 and 6% (presumed to include a component of base flow, i.e. groundwater), the remainder going to evaporation and evapotranspiration.

Although the potential water available for storage is only a small proportion of the total rainfall, capture and recharge of only an additional 1% of rainfall would equate to a rise in water table of 250 mm over the whole area (assuming a storage capacity of 2%). In practise this would equate too much bigger rises, focussed around recharge structures. Rainfall distribution is however very variable and frequently is 50% above or below the average. Again, making use of groundwater storage can smooth out the impacts of this variability and provide a sustainable source of water for human and livestock consumption as well as irrigation.

In another project in Thailand, India, the influence of a percolation pond on the water balance in the Agrahara Valavanthi micro-watershed, Namakkal District, (TWAD, 1998) was studied. The pond lies on weathered basement granitic gneiss and has a catchment area of 12.8 km^2 and a capacity of 7770 m^3. It was calculated that during the period monitored (October 1997 to

February 1998) the percolation pond contributed 20% of the total recharge to the micro-watershed. Evaporation from the open water surface was assumed to be 5% of the infiltration volume. This equates to an average evaporation rate of about 1.5 mm/d, which is low in comparison to figures of 5.5 mm/d for open water evaporation reported elsewhere in Karnataka (Batchelor et al., 2000). See Section 2.2) and about 10% of the recharged volume in a study in the Amravati District, Maharashtra (CGWB, 2000). These projects used a variety of methods to quantify the water balance and the impacts of percolation pond and other structures. In the study in Karnataka, measures of the beneficial impacts from artificial recharge included a rise in water table sufficient to rejuvenate a defunct borehole fitted with an electric pump and created a body of potable groundwater which had been of unacceptable quality for over four years.

Other studies have focussed on quantifying the volumes of water infiltrated into aquifers, balanced against the volumes flowing into the structures and losses to leakage and evaporation. One such study at the IIT campus in New Delhi (CGWB, 2000) demonstrated high recharge efficiencies with evaporative losses ranging from only 0.3 to 5%.

3.3 HYDROGEOLOGICAL CRITERIA

3.3.1 General criteria

The physical success of an artificial recharge scheme depends largely on the local hydro geological 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:

- Hydro geological properties of the aquifer and the overlying formations.
- Physical and hydraulic boundaries of the aquifer.
- Depth to aquifer.
- Groundwater quality

The hydro geological conditions in the surface and unsaturated zones 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 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, storability, leakance, porosity, etc.) and its thickness and aerial extent. The receiving formation must have sufficient permeability and thickness to accept recharged water at a designated rate (O'Hare et al., 1982). 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. An ideal combination of parameters, where storage and treatment of recharge water is required, would be an aquifer with a high enough hydraulic conductivity to accept high infiltration rates, but with sufficient clay content for sorption of trace elements and filtration to occur (Murray and Tredoux, 1998).

The depth to water table will determine which artificial recharge methodology is most applicable for the site. When an aquifer is located at, or near to the ground surface, water spreading may be applied, e.g. by flooding or recharge basins. When a thin layer of less permeable material covers an aquifer, this layer may be ripped open by ploughing or harrowing after which the same spreading methods can be used. If however, the less permeable layer is thicker, simple flooding methods can no longer be used, and recharge may only be applied via pits or trenches if they can be made deep enough to penetrate the confining layer. Where the low permeability layer is of greater thickness, or the receiving aquifer is located at depth, recharge can only be accomplished using wells or boreholes.

Aquifers with low storage capacity may be only limited potential to accept additional water through Artificial Recharge. 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 filled by both natural and Artificial Recharge. Increased capacity to accept additional natural recharge was demonstrated in a study of sustainable groundwater development in an area underlain by Deccan basalts, in Maharasthra, India (Macdonald et al., 1995). Although additional natural recharge occurred, the rate of abstraction still exceeded the rate of replenishment and groundwater levels continue to fall.

In addition to these subsurface characteristics, a full feasibility assessment should also consider the impacts of the scheme on the hydrological and ecological regime in the area including the impacts on existing users of groundwater, the contribution of base flow to streams and the proximity of potential sources of contamination.

3.3.2 Criteria relevant to geological setting

ALLUVIUM

Alluvium can consist of fluvial, marine and lacustrine deposits ranging in thickness from a few tens of metres to kilometres. 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 at shallow depth 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. Where there is storage space in the aquifer, either natural or from over-development, the source of recharge water is likely to be intermittent and short lived and effective capture and storage structures are needed.

ALLUVIUM OVERLYING HARD ROCK

These fluvial and collegial deposits are found in the upper (relatively high energy) reaches of rivers. Deposits are sandy to coarse and form aquifers up to a few tens of metres thick. The underlying aquifers usually consist of fractured igneous and metamorphic rocks, in hydraulic connectivity with the overlying alluvium. This hydro geological situation is distinguished from hard-rock aquifers with thin cover (next section), in that the alluvium is sufficiently thick to form an aquifer in hydraulic contact with the underlying fractured rock aquifer. It therefore forms a mechanism for absorbing and storing intermittent rainfall, which can then percolate to the underlying aquifer.

HARD ROCK WITH THIN SOIL/WEATHERED ZONE

As above, but without the benefit of storage in the overlying porous material. The aquifer is the fractured bedrock, comprising igneous, metamorphic and volcanic rocks. There is also only limited storage in the hard rock aquifer, which can therefore be depleted more rapidly. The soil/weathered zone is too thin to store useful quantities of water other than at a very local scale.

CONSOLIDATED SANDSTONE AQUIFERS

These are porous/fractured aquifers that can have good storage capacity and hydraulic properties. Recharge, both natural and artificial, is determined by the surface layer. If the soil is developed from the sandstone then recharge capacity will be high, but can be reduced if overlain by alluvial deposits. Where the surficial layer is permeable and infiltration capacity is high, vulnerability to contamination is also high. Additionally, if the permeability of the aquifer is high then recharged water is likely to be dissipated quickly and may even be lost to base flow in rivers, possibly the source of the recharge water. A good understanding of the hydraulics of the aquifer is therefore needed to ensure that the net results of artificial 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

Similar arguments apply to carbonate aquifers that apply to the sandstone aquifers, except that the main storage and flow is in solution-enhanced fractures. The ratio of fracture flow to intergranular flow will vary considerably from low ratios in porous limestone (e.g. oolites) to high ratios in indurate limestone where flow is karstic. The response of karstic aquifers will be the most extreme in terms of both contamination and dissipation of recharged water. 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.

3.3.3 Ground Water quality

Ground water where affected by anthropogenic impacts is usually quality regard as having excellent quality from the chemical, turbidity and microbiological perspectives. Ground water is the source of spring and bottled water. These high quality aspects result from the natural filtering and microbiological "treatment" afforded 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 will however vary from one rock try to another, and also within aquifers along groundwater flow paths. Where groundwater flow is relatively rapid (metres to 10s metres/year) then groundwater quality is likely to be very high. However, with longer resistance times and depending on climate and host geology naturally occurring toxic, chemicals may become dissolved in the groundwater e.g. Arsenic, Fluoride, as well as unacceptable concentrations of elements such as chloride iron and manganese. The hydrogeochemical environment and availability of elements together with the residence time will determine the concentration of dissolved solids so it is important to measure the pH dissolved oxygen concentration as well as the radix potential as well as the chemical constituents in natural groundwater.

The natural quality of groundwater will be offered as a result of the wide range of anthropogenic activities; the most significant being groundwater obstruction, 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 artifical recharge in a particular hydrogeological environment it is therefore important to understand the natural quality of the groundwater and the impacts of man's activities and the processes controlling the resultant quality. From this basis the likely impacts of artificial recharge on both the in site groundwater and the water recharged can be predicted and maintained to avoid unacceptable impacts.

In general where water table aquifers have been exploited for irrigation and rural use, decline in water levels are eventually accompanied by deterioration of water quality. Artificial recharge with surplus runoff through surface infiltration structures with usually provide high quality water that will not only replenish resources but also improve quality through dilution or can be used to provide a hydraulic barrier to lateral soling interimum (eg the coastal sand dune recharge schemes in The Netherlands)

Where treated drinking water or storm water is injected into confined aquifers, often 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 nitrate removal and attenutation of some organic compounds.

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

Table 1 Factors affecting the technical effectiveness of Artificial Recharge schemes in relation to hydrogeological setting

	ALLUVIAL AQUIFERS	ALLUVIUM OVER FRACTURED HARD ROCK AQUIFERS	FRACTURED HARD ROCK WITH THIN SOIL/WEATHERED ZONE	CONSOLIDATED SANDSTONE AQUIFERS	CARBONATE AQUIFERS
EXAMPLES OF ARTIFICIAL RECHARGE SCHEMES	Terai region, Nepal and adjacent area in Uttar Pradesh, India Phoenix, Arizona, USA Atlantis, S. Africa	Alwar, Rajasthan, India Meshana District, Gujarat, India	Saurashtra, Gujarat, Coimbatore, Tamil Nadu Andhra Pradesh, India Karnataka, India Maharasthra, India	Loftsome Bridge, Yorkshire, UK	Lytchett Minster, England, UK Israel
GENERAL CHARACTERISTICS	Fluvial, marine and lacustrine deposits ranging in thickness from a few tens of metres to kms. Layered sequence of clays, sands and gravels as well as some calcareous layers. Lower reaches of rivers forming flood plains, so low relief.	Fluvial and colluvial deposits in upper reaches of rivers. Deposits are sandy to coarse and form aquifers a few tens of metres thick. Underlying aquifer is fractured igneous and metamorphic rocks, usually in hydraulic connectivity with the overlying alluvium.	Aquifer is the fractured bedrock comprising igneous, metamorphic and volcanic rocks. Soil/weathered zone is too thin to store water other than at a very local scale.	Aquifers with a matrix of sand grains held together by a cement (e.g. calcite silica) or indurated by metamorphic processes. This results in a wide range of porosity/fracture ratios and hence hydraulic properties	Aquifers with hydraulic propertied controlled by the solubility of the rock. Solution enhanced fractures can result in karstic flow.
HYDROGEOLOGY					
PHREATIC OR CONFINED	Phreatic if permeable layer at surface, becoming more confined with depth. Layered aquifers with variable connectivity.	Coarse nature of alluvium usually results in phreatic conditions, the hard-rock aquifer being in hydraulic connectivity.	Usually phreatic in the hard-rock aquifers, depending on interconnection of fractures.	Phreatic where there is no alluvial cover or a confining clay layer	Phreatic where there is no alluvial cover or a confining clay layer

	ALLUVIAL AQUIFERS	ALLUVIUM OVER FRACTURED HARD ROCK AQUIFERS	FRACTURED HARD ROCK WITH THIN SOIL/WEATHERED ZONE	CONSOLIDATED SANDSTONE AQUIFERS	CARBONATE AQUIFERS
POROSITY AND STORAGE	Porosity high but effective storage restricted to sand and coarse layers.	High porosity and storage in the alluvium, only limited by the thickness. Low storage capacity in fractures in the hard-rock but drainage from the alluvium can maintain well yields.	Low storage capacity in fractures. If this storage is depleted through overdraft then additional storage can be created, to be filled in subsequent wet season.	Proportion of storage in the matrix of these aquifers will be determined by the porosity and degree consolidation and fracturing	Proportion of storage in the matrix of these aquifers will be determined by the porosity and degree consolidation and solution-enhancement of fractures
PERMEABILITY AND FLOW	Flow mainly in coarser horizons so their inter-connectivity, as well as the connectivity to the recharge zones will determine the flow paths. Low hydraulic gradients will result in slow groundwater flow.	Flow in alluvium will drain towards streams rapidly, depleting resources. Hard-rock aquifers will generally have low fracture permeability, except in large fracture zones.	Flow to wells in hard-rock will be in fractures; the greater the number the greater the yield and speed of refilling the well.	Permeability and flow will be determined by the porosity and degree consolidation and fracturing.	Permeability and flow will be determined by the porosity, the degree of consolidation and solution-enhancement of fractures.
GROUNDWATER LEVEL FLUCTUATIONS	Because of high storage capacity, fluctuations will small; a few metres. If water table is near the surface then there is limited scope for recharge. Pumped drawdown can create additional storage if managed carefully.	If water-table is in the hard-rock aquifer then it will generally respond quickly to pumping and recharge, but within a restricted radius due to the low permeability. When the water table is in the alluvium then the same arguments apply as discussed in the box to the left.	Groundwater levels will rise and fall rapidly in response to recharge and pumping.	Where the porosity of the aquifer is high, the groundwater fluctuations will be relatively subdued in response to pumping and recharge	Where the fractures provide the main porosity, groundwater fluctuations will be rapid.

	ALLUVIAL AQUIFERS	ALLUVIUM OVER FRACTURED HARD ROCK AQUIFERS	FRACTURED HARD ROCK WITH THIN SOIL/WEATHERED ZONE	CONSOLIDATED SANDSTONE AQUIFERS	CARBONATE AQUIFERS
INFILTRATION CAPACITY	High if surface layer is sandy but low if there is a high clay content. Coarse material needed for full zone of recharge. A clay, or other low-permeability layer, at a shallow depth will restrict recharge.	Good in sandy alluvium, which can store water and hence facilitate infiltration into the underlying fractured rock	Capacity limited by the number of open fractures so runoff can be large.	Very high where there is no cover and the soil has developed from the sandstone.	Very high where there is no cover. Soil development is usually very thin and surface runoff minimal
QUALITY ISSUES	Groundwater quality good in active flow zones but can deteriorate where flow is slow or from saline intrusion. Where there is little natural groundwater movement, the concentrations of elements such as iron, magnesium, arsenic and fluoride can exceed acceptable limits. AR can improve water quality by dilution or displacement. Vulnerability to pollution depends on the permeability of the surface layers.	Groundwater quality good in active flow zones. Permeable alluvium will be vulnerable to pollution.	Groundwater quality good in active flow zones but vulnerable to rapid pollution through fracture flow. Thin soil cover will only provide limited protection.	Very good quality groundwater where actively recharged but susceptible to contamination, particularly where soil cover is thin	Very good quality groundwater where actively recharged but extremely susceptible to contamination.

	ALLUVIAL AQUIFERS	ALLUVIUM OVER FRACTURED HARD ROCK AQUIFERS	FRACTURED HARD ROCK WITH THIN SOIL/WEATHERED ZONE	CONSOLIDATED SANDSTONE AQUIFERS	CARBONATE AQUIFERS
METEOROLOGY					
RAINFALL INTENSITY	Surface flow will occur if infiltration rate is exceeded or soil is at capacity. Widespread flooding will result in flood plain deposition.	Rapid runoff from adjacent bedrock during intense rainfall may cause erosion of alluvium and soil.	Rapid runoff during intense rainfall may cause erosion of soil.	Infiltration capacity likely to be high so natural infiltration and recharge likely to be high also. Extreme events may cause soil erosion and provide potential water for artificial recharge.	All but the most extreme events will infiltrate. Thin soils are easily eroded.
EVAPO-TRANSPIRATION	Rainfall and evaporation will vary considerably in both time and space. Annual variability of rainfall is high, so average figures need to be used accordingly. The components of the water balance in three watersheds in Karnataka that follow are given as examples only and cannot be applied widely. (Batchelor et al., 2000). Long-term annual average rainfall is 520 mm and Penman potential evapotranspiration of 1750 mm. Indicative estimates of the water balance at the field scale in non-irrigated areas are: evapotranspiration from the soil, 45%; evapotranspiration from cropped areas, 25%; surface runoff, 10%; and recharge to groundwater, 10%. Open water evaporation will occur at full potential rate for standing water bodies, about 2000 mm/year (5.5 mm/day). Evaporative losses from tanks can be reduced by increasing the depth of water; hence reducing the surface area/volume ratio. Underground storage through artificial recharge will obviously reduce evaporative losses to zero, once infiltrated.				

3.4 TOPOGRAPHY

Topography is an important factor to consider with regards to recharge site selection. It permits or retards runoff, thus influencing recharged water infiltration rates and amounts. Specific attention is needed in the case of recharge to unconfined aquifers, where water tables will rise during recharge and may intersect the ground surface. This is especially important in cases where groundwater flow paths are difficult to predict, e.g. in fractured or karstic limestone formations (Australian Water Resources Council, 1982).

Groundwater levels tend to form a surface that is sub-parallel to the topography; greater depth to water at the interfluves than in the valleys. Areas of low topographic relief therefore tend to have very low groundwater gradients compared to areas with higher relief. This factor needs to be considered in relation to movement of water away from the location where it is recharged artificially. The depth to groundwater is also generally related to topography, the water table being shallower in areas of low relief and hence less available storage.

3.5 SOURCE WATER CONSIDERATIONS

A prerequisite for the production of artificial groundwater is 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, wastewater, groundwater or water for potable supply.

3.5.1 Surface water

Surface water can be a consistent source of recharge water depending on the climatic situation. Under humid conditions moderate variability in river flows can be expected, and perennial rivers are predominant. Under arid or semi-arid conditions ephemeral rivers prevail.

River water can carry considerable quantities of silt in suspension, the amount depending on the turbulence and ‘energy’ of the river. Lowland, slow moving rivers 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. In lakes, water is not flowing significantly and is usually 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 as it recharges, through physical and biochemical processes.

3.5.2 Storm-water runoff

Urban centres 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, porous pavements and wetlands are recommended for watershed areas (Murray and Tredoux, 1998).

In rural areas, intense rainfall can generate surface runoff from agricultural fields. In some areas (e.g. Saurashtra, India, dug-well recharge movement) this runoff is channelled into large diameter hand dug wells to directly recharge the aquifer. 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 dissolved constituents.

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. Highest contamination load can be observed in the “first flush”, which should be diverted to waste to improve quality. Rainfall harvesting in the form of roof watershed runoff is most likely the best quality storm water runoff to use, whilst runoff from industrial areas can often contain a high load of contaminants.

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.

3.5.3 Wastewater

Waste 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 ground water quality (Bouwer, 1996). 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 ground water, 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 breaks the objectionable “toilet-to-tap” perception that is illogically not connected with disposal of treated wastewater to rivers that are subsequently used downstream as sources of potable water. 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.

Wastewater 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 (Dillon and Pavelic, 1996). 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, high salt content and trace elements including selenium, uranium, boron and arsenic (Committee on Ground Water Recharge, 1994).

Use of municipal wastewater for agricultural irrigation is widely established in Mexico (Chilton et al., 1998). 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 so helping to prevent pollutants such as organic carbon, nutrients, heavy metals and pathogens form 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).

3.5.4 Groundwater

In areas where potable groundwater is only available on a seasonal basis, it can be used as a source of recharge water to resolve seasonal supply and demand imbalances. In these special circumstances, groundwater may be abstracted from a low-yielding aquifer and stored in an adjacent or overlying aquifer. This water is then available at the point of demand in periods when the use of groundwater or river water resources are restricted, or to meet peak demands, e.g. during summer, particularly in coastal holiday resorts (Jones et al., 1998).

Where groundwater of non-potable quality is used as the recharge source, the usable quantity of water recovered is affected by the degree of mixing with ambient groundwater during storage. Increasing the time between recharge and withdrawal increases the mixing between introduced and ambient groundwater (Dillon and Pavelic, 1996). As with surface water resources, a distinct advantage of using untreated groundwater as a source of recharge water is the relatively low cost (Pyne, 1995).

Untreated groundwater is frequently of excellent quality. However, when recovered, the stored groundwater often requires treatment to meet potable standards (Pyne, 1995). Where recovery efficiency is acceptable, it is more cost-effective to store and recover treated drinking water rather than untreated groundwater as no water treatment is required after recovery.

3.5.5 Potable water

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, were 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 (Mukhopadhyay and Al-Sulaimi, 1998) 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.

3.6 METHODOLOGIES TO ASSESS TECHNICAL EFFECTIVENESS OF ARTIFICIAL RECHARGE SCHEMES

3.6.1 Introduction

In general, the aim of artificial recharge facilities is to augment groundwater resources but effectiveness will vary considerably between schemes. If the artificial recharge scheme is effective, a rise in groundwater level, or a reduction in the rate of the decline, should be observed. Seasonal wells should be able to provide water for longer periods and the energy consumption for lifting water will reduce. If artificial recharge schemes contribute to groundwater storage, baseflow, and hence surface water availability, an increasing vegetative cover could result in a reduction in soil erosion and a general improvement in fauna and flora, e.g. influx of migratory birds, wildlife etc.

However, additional groundwater abstraction for irrigation based on a misconception of the quantity of artificial recharge that is occurring, will only lead to exacerbation of declining groundwater levels. Small reservoirs, for example, will have high surface area to volume ratios, which can result in high evaporation losses. In such a case, the water in the reservoir may provide a valuable resource for fishing, bathing, livestock watering etc. but the contribution to groundwater augmentation may be limited.

Hence, in the context of sustainable groundwater management, it is essential to assess the effectiveness of artificial recharge schemes in terms of their ability to recharge the aquifer. However, effectiveness can be difficult to measure directly. A detailed water balance study is the only approach delivering a quantitative estimate of the contribution of a scheme to groundwater recharge, the many variable components being shown in Figure 1. Water balances are discussed further in Section 3.3.2, including some examples of studies that have been undertaken in India in a variety of different hydrogeological settings. In addition to a full quantitative water balance study there are methods that will be indicative of the effectiveness of artificial recharge schemes, both relatively and temporarily at the reservoir and watershed scales.

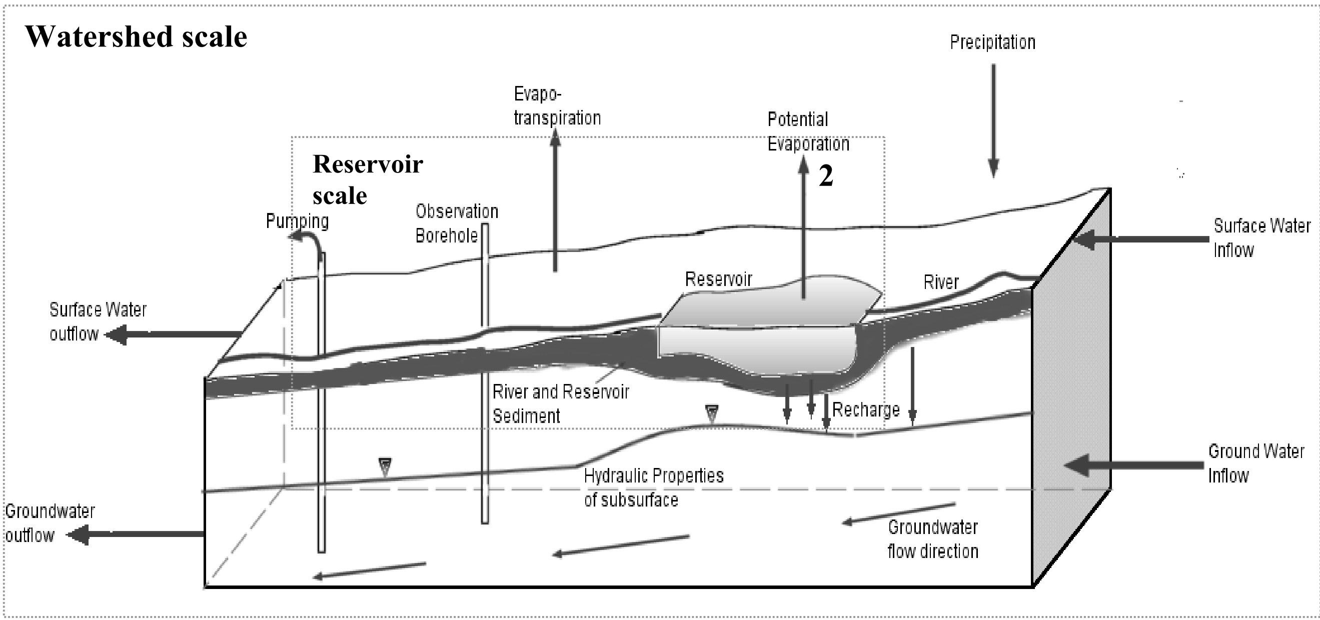

Figure 2 Components of the water cycle at reservoir and watershed scales

3.6.2 Watershed scale

The components of the average annual water balance at a watershed scale are precipitation, evapotranspiration, runoff (surface runoff and baseflow) and change in groundwater storage. This can be generalised into:

Precipitation = Evapotranspiration + surface runoff + baseflow +/- change in storage (1)

Thus, the amount of water going into a watershed in a given time equals the amount of water leaving the watershed in the same period, plus or minus the change of storage within the watershed during this period.

Equation (1) demonstrates that increases in groundwater recharge, and hence groundwater storage, can only be achieved through a reduction in evaporation or a reduction in runoff from the watershed, assuming no change in the annual average precipitation. Therefore, the average annual surface runoff from a watershed is indicative of the scope for developing additional artificial recharge schemes and gives a quantitative estimate of the amount of water available for recharge.

Arresting surface runoff with artificial recharge structures increases the potential for transfer of water into storage in the aquifer and reduces the quantity available for surface runoff. Where runoff is seasonal (e.g. monsoonal climate), surface runoff can, not only be very destructive but can also be largely lost to evaporation after flood events. Good water resource management can result in more water going to groundwater storage and hence increasing baseflow to streams and reducing its variability. This may lead to ephemeral streams becoming perennial.

To obtain a groundwater balance for a watershed, good quality hydrological and hydrogeological information is needed. Of the terms in the water balance equation, data on precipitation and run-off can be measured directly, using rain gauges and river flow gauges respectively. Hydrograph separation then can be used to separate the baseflow and the surface runoff. If hydrographs are available before and after artificial recharge structures are installed, quantification of surface water and baseflow components of the annual runoff will give an estimate on the effectiveness of artificial recharge structures in the watershed.

Evaporation is more difficult to quantify and involves more sophisticated instruments such as weather stations and evaporimeters. The reader is referred to (Shaw, 1996) and [Gunston, 1998] for a detailed summary of methodologies.

The change in groundwater storage is measured by the rise or fall of the water table in the watershed. Estimates of specific yield or effective porosity can be obtained through aquifer testing or applying known values, and hence the change in storage can be calculated. In the case of a confined aquifer the change of the piezometric surface has to be recorded and multiplied by the storage coefficient of the confined aquifer to obtain the change in storage.

Numerical modelling of the hydrogeological regime can be applied on the basis of the known water balance components. Inputs, like precipitation, and outputs, like evapotranspiration, baseflow and abstraction, have to be measured or estimated to enable the model to simulate groundwater levels. The model is verified by comparing the computed water levels with observed ones and then can be used to simulate the response of an aquifer to various amounts and locations of artificial recharge. This can then be used as a tool to manage the aquifer.

However, it has to be noted, that estimates of the water balance components from individual techniques will nearly always be subject to some error. This will be evident from, amongst other factors;

- the wide spatial variability of rainfall and runoff events, especially in the more arid regions,
- the widespread variability in soil profiles and hydrogeological conditions,
- the inadequacies of the hydrogeological databases.

3.6.3 Reservoir scale

The water balance of an individual structure needs to take account of the supply to, and discharge from the reservoir, along with the changes in the amount of storage within both the reservoir and the underlying aquifer. The water balance can be summarized as:

Precipitation + Surface (and groundwater) inflow = Evaporation + Recharge + Surface outflow (overflow, leakage, abstraction)+/- Change of volume of water in the reservoir (1)

The water balance for a reservoir can be simplified during periods of no precipitation and when surface inflow and outflow can be neglected. A further simplification can be made if losses due to leakage, abstraction etc can be neglected, and if the reservoir is under effluent conditions in relation to the aquifer, then the water balance can be summarized as:

Groundwater Recharge = Change of volume of water in the reservoir - Evaporation (2)

Equation (2) demonstrates that the share between evaporation and groundwater recharge will determine the effectiveness of the artificial recharge scheme. If evaporation were theoretically 0 then the change in volume of water in the reservoir would equal the groundwater recharge. This could be monitored from a change in the water level in the reservoir. At the other extreme, a reservoir might be silted up when the fall in water level would be entirely due to evaporation, i.e. groundwater recharge would be 0 and the scheme would be ineffective.

To quantify evaporation and groundwater recharge, different methods of various complexities can be adopted. The method(s) selected to estimate the effectiveness of artificial recharge structures is governed by the required accuracy and the funds available. Some commonly used methods are summarized below. For a more detailed description of available methods the reader is referred to (Kraatz, 1971), (Lerner et al., 1990) or (Huisman and Olsthoorn, 1983).

RESERVOIR WATER LEVEL MEASUREMENT

A simple and direct approach is to record periodically the change in water level in a reservoir. The readings are converted to volumes of water by a calculated depth-volume relationship. The volume of water that evaporates from the open water surface is subtracted from the calculated volume and thus, the volume of water that seeps downward during a specified time interval is obtained. Evaporation is either computed from available meteorological data or it is estimated from measurements from an evaporimeter installed at a meteorological station. The accuracy of estimation of the recharge from the reservoir depends on the accuracy of the estimates or measurements of evaporation. Measurement of evaporation can have large errors and this uncertainty needs to be quantified in comparison to the rate of water level decline.

GROUNDWATER LEVEL MONITORING

By monitoring the groundwater levels in wells and boreholes adjacent to (or underlying) the reservoir, the size and shape of a ‘groundwater mound’ resulting from recharge can be estimated. If the specific yield of the aquifer is measured or estimated then the volume of recharge can be calculated. This method suffers from requiring extrapolation of several estimates from a very few data points and that the mound is dynamic in that it is both increasing and decaying at a variable rate depending on its hydraulic head relative to the surrounding water table.

CHLORIDE MASS BALANCE

The chloride mass balance method is based on the assumption that there are no sources or sinks of chloride in the reservoir other than natural input from precipitation and runoff and that there is no loss of water from the reservoir other than evaporation and recharge. The total chloride content of the reservoir water at any time is estimated from the volume of water in the reservoir and its chloride concentration, which is measured regularly (Sukhija et al., 1997). There is no loss of chloride by evapotranspiration and thus, the concentration increases as evaporation proceeds. The water seeping into the ground however exhibits a constant chloride concentration. Thus, by measuring the volume of water and its chloride concentration over time, an estimate of the evaporation from the reservoir can be made and consequently, the percentage recharge can be calculated.

SALT PENETRATION TECHNIQUE

The method was developed by (Bouwer and Rice, 1968) and uses salt as a tracer which is spread on the reservoir bed as crystals and left. A conductivity probe pushed into the ground records the position of the saline seepage front with time and depth, on the basis of which the seepage rate can be calculated. It might be possible to use other tracers, such as radioisotopes (Lerner et al., 1990).

STABLE ISOTOPE METHOD

The stable isotope method uses the enrichment of deuterium and oxygen-18 in the reservoir water due to evaporation. This enriched water can be used as a tracer, thus delineating the area influenced by the artificial recharge structure. The method is relatively sophisticated and expensive.

INFILTROMETERS

Two concentric steel rings are driven halfway into the ground of the empty reservoir. A measured volume of water is put into the protruding part of the ring and the rate of fall of water level is monitored. The extrapolation of data obtained from infiltrometers requires a great deal of judgement and is not entirely reliable.

SEEPAGE METRES

Seepage meters have been developed to measure reservoir losses directly. They consist of a cylindrical steel vessel, closed at the top and open at the bottom, which is pressed 2-3 cm into the floor of the filled reservoir. The infiltration rate is measured by constant or falling head techniques. In the former, the vessel is connected with a hose to a plastic bag of known volume, floating just below the surface. This results in an equal pressure head to drive the seepage inside the vessel and outside the vessel. The seepage rate can thus be determined by measuring the change in volume of the bag over time.

The falling head technique involves a container, which supplies recharge to the vessel. The water level in the container is at a height Δ above the water level in the tank. The rate of downward percolation in the vessel can be measured from the decrease of Δ with time. Both water levels, in the container and in the reservoir are then recorded and plotted against time. A comparison between the two resulting curves will yield the seepage rate for the reservoir at the point of intersection between the two curves.

Seepage meters are quickly and easily installed, but disturbance of the soil during insertion of the meter can cause indicated seepage rates to be higher than actual.

EMPIRICAL FORMULAE

There are many empirical formulae used to calculate seepage losses from reservoirs, however these are mainly site specific as they are based on observations within one region. Thus, these may not be valid for reservoirs in other regions, with different field conditions (Lerner et al., 1990). A summary of empirical formulae used in various parts of the world to calculate seepage from reservoirs is given by (Kraatz, 1971).

MODELLING

Leakage from a reservoir into an aquifer can be simulated with numerical models. Different model techniques have to be used according to the prevailing field situation, e.g. the regional water table is far below the reservoir and flow through the unsaturated zone has to be taken into account or the reservoir is hydraulically connected with the water table and saturated flow prevails. Some readily available computer codes like the three-dimensional finite-difference groundwater model, MODFLOW (McDonald and Harbaugh, 1988) include subroutines to simulate leakage between a reservoir and an underlying groundwater system as the reservoir area expands and contracts in response to changes in reservoir stage (Pfenske et al., 1996).

Numerical models can be used to predict infiltration rates in response to the depth of water in the reservoir, to the difference between the water level in the reservoir and the groundwater table or to different conductivities of the reservoir bed. However, accurate knowledge of the subsurface conditions and their hydraulic parameters is needed as well as the parameters of the reservoir water balance in order to derive meaningful results.

3.6.4 Method selection

Best results are most likely to be obtained from using a combination of methods that approach the problem from different directions giving results that can be compared analytically. If estimates of the effectiveness of a large number of reservoirs are needed then the best approach may be to undertake a large number of relatively cheap and simple measurements that can be related to detailed studies of one or two sites.

Selection of the most appropriate method(s), from those described above, will depend on the individual sites and the resources and skills available. Instrumentation can range in sophistication from a simple staff gauge in a stream or reservoir to a digital recording device that sends the data recorded to the scientist's office by telemetry. The former can be read periodically by someone with no prior hydrological training but the siting and installation of the gauge and the interpretation of the results needs professional supervision. Installation of more sophisticated technology to record water levels and meteorological parameters requires greater professional knowledge. Both remote and densely populated locations pose potential problems for data recording including, access, instrument failure, security and loss of records or destruction of installation by natural causes. The best solution for individual situations will depend on the relative cost of equipment and staff, the availability of staff with the required level of training, availability of equipment and maintenance backup etc. To produce a methodology that can be widely adopted as a useful measure of recharge effectiveness it must be cheap, simple and of demonstrable value to the users.

4 Socio-economic factors determining the effectiveness of Artificial Recharge

4.1 SETTING THE SCENE – INCENTIVES FOR MANAGEMENT

Any evaluation of artificial recharge needs to recognize the major structural changes occurring in society and the incentives they create for management of any type. Some of the key starting points that are generally assumed for artificial recharge in rural areas through community-based initiatives include:

- A Stable society: A starting assumption in most attempts to initiate management is that communities are stable and have a strong incentive to manage water resources because they form the basis for current livelihood and economic systems. This assumption may be flawed due to a variety of overlapping considerations including:
    - Demographic transition (India to be >50% urban in the next decade). Many "rural" communities are no longer rural or dependent on rural forms of livelihood. Farmers in Gujarat, for example, often comment that they know water levels are falling but that it makes little difference to them because the next generation will be urban. In addition, production based on unsustainable groundwater extraction is often used to pay for education and other activities that help to finance this transition. As a result, their concern is maintaining current income rather than the longer-term sustainability of the water resource base.
    - Economic diversification: The presumption in most watershed development is that agriculture dominates the rural economy and that most water users have a strong incentive to ensure the sustainability of the water resource on which this economy is based. This may no longer be the case in many areas. In Gujarat, for example, the economy is increasingly industrialized and integrated in regional and global trading systems.
    - Economic fluctuation/globalisation: In many situations, farm incomes fluctuate substantially due to changes in regional or global market conditions. Because the uncertainty of income is high, farmers have short time horizons with regard to economic returns from water management investments. This can reduce their incentive to, for example, invest in artificial recharge activities where the benefits often accrue gradually over longer periods of time. In addition, benefits have to be substantial because there is a significant risk of loss. As a result, lower level benefits (such as a reduction in pumping costs due to higher water levels) may provide little practical incentive.
- Tangible benefits that accrue to those investing in recharge: Many of the benefits from artificial recharge are long-term and accrue to all those utilizing an aquifer as opposed to the smaller groups who may contribute directly to an artificial recharge scheme. This might be the case, for example where higher water levels reduce pumping costs on a regional basis but make little practical difference in the economics of farm operations (a situation common in parts of India where farmers currently do not pay for the power they consume). In addition, many of the benefits, such as increases in downstream baseflow, wildlife habitat, etc. may be intangible or not directly valued by the communities actually using an aquifer. An example of this may

be present in the case of migratory bird populations where the global environmental community has strong interests but the local communities do not share these.

- Scale mismatches: The community (village) is implicitly assumed to be the management unit but the benefits from artificial recharge often accrue at the scale of aquifers or regions. Smaller groups may also form within a village community to build structures to enhance recharge. Scales may match well in low permeability environments where recharge directly influences water levels or water availability in local wells. The potential for scale mismatches probably increases in high transmissivity environments where lateral flow rates disperse the impact of recharge.

The above types of considerations are not present in all situations where artificial recharge represents a potential solution to groundwater over-extraction problems in rural agricultural areas. They should, however, be evaluated in such areas because the incentives they create greatly influence the viability of different institutional approaches to AR. Where village communities are relatively stable and remain heavily dominated by agriculture, communities may have strong incentives to contribute to artificial recharge activities. In areas where populations are in a state of transition to more urban livelihoods, however, different institutional arrangements may be necessary. Urban areas often have stable governance structures (such as municipal authorities) above the community or village level. These provide a very different foundation for management than the community-based structures found in rural areas. The nature of the stakeholders is also often different. Rather than individual farmers, for example, institutional users (corporations and municipal supply authorities) are often major players. In addition, management objectives are often different. Instead of supply, the objectives of recharge may include quality improvement and control, subsidence mitigation, and so on.

The following subsections focus on rural situations where stakeholder participation and community incentives are central. The institutional and community dimensions of artificial recharge in urban and transitional areas are, however, a critical area for further research. The main point to note here is how different they are likely to be. In addition, it is important to recognize the critical need for research on transitional areas. In such peri-urban regions, needs are changing, uses are changing, incentives for management are fluid and the institutional infrastructure for management is undeveloped. The zone of influence of urban areas often extends hundreds of kilometres into regional that are classified as “rural.” This influence can be direct (in terms of water transfers) or indirect in terms of the economic incentives and job opportunities they create. In either case, the transitional areas are probably some of the most important and least well understood from a water management perspective within which artificial recharge could play an important role.

4.2 INSTITUTIONAL ARRANGEMENTS

A variety of approaches has been employed for implementing natural resource management activities such as artificial recharge, with responsibilities resting (to varying degrees) with the state, local government, development agencies, NGOs and local people. A dominant institutional theme emerging over the last two decades in natural resource management has been decentralisation, in tandem with efforts to promote a more ‘bottom-up’, participatory planning process (Carney and Farrington, 1998). As the poor are disproportionately dependent on common pool resources, improvements in decentralised management - whether in equity of rights and responsibilities, in resource productivity, or in its sustainability – can contribute substantially to their livelihoods.

Three distinct institutional approaches have varying legitimacy and potential capacity to contribute to such improvements (Farrington J et al., 1999).

- **Informal, often traditional user groups**, generally enjoying *de facto* rights of access only. In some countries steps have been taken to codify customary rights, though (more typically) the state is reluctant to transfer access rights to local communities or individuals. In view of the difficulty in applying formal regulatory and economic instrument approaches to natural resource management in countries such as India, attempts to encourage/re-instate systems of common property management have received considerable attention (e.g. in forestry). DFID is currently funding a research project in India looking at the potential for user group management of groundwater under common property.[1]
- **Public administration**, increasingly in collaboration with local communities. Moves towards forming natural resource management *partnerships* with communities or 'user groups' for particular resources are found in many countries. In India, for example, this is now the preferred model for watershed development - in which artificial recharge of groundwater plays an important part - though local government involvement is now increasing (see below).
- **Local government**, operating independently of government departments, but drawing on services from them. In many African countries (e.g. Ghana; Malawi; South Africa), local government is now taking on responsibilities in water supply and sanitation provision, not as a provider but as a 'facilitator' in a demand driven process. In India, where *administrative* decentralisation is now a core feature of watershed development (under the partnership model described above), growing attention is focusing on the interface with *political* decentralisation through the *Panchayati Raj* local government reforms (see below).

Why the emphasis on decentralisation? In many countries, state led approaches to natural resource management have been monolithically blamed for the degradation of natural resources. As a consequence, the state is advised to adopt a facilitative rather than a leadership role. As the classification (of decentralisation approaches) above implies, the state then becomes part of a far more heterogeneous development process in which a coalition of different actors and institutions is involved.

A re-evaluation of the role of the state has occurred in many other sectors and sub-sectors, including water supply. For example the 'Dublin Principles' of 1992 represented a major shift towards achieving sustainable water supplies through promoting demand-led, as opposed to supply-led, development. Stimulating demand, achieving full cost recovery and building community ownership became key goals, and the concept of a 'demand responsive approach' emerged and was promoted firstly by the World Bank, and then by many others, including DFID.

In India, the arguments for decentralisation that emerged in the late 1980s and early 1990s stemmed from a perception of (a) a downward spiral of resource degradation; (b) the inability of natural resource users to organise themselves adequately to reverse degradation; and (c) the limited effectiveness hitherto of the state in resource use planning and service provision (Farrington J et al., 1999). Their translation into new policy directions came about firstly in 1987 with the publication of the National Water Policy (NWP), aimed at developing a

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[1] DFID-KaR project, Community based management of groundwater resources in rural India' (R8058). This project complements the AGRAR research in a number of important respects. In particular, by investigating the role locally devised rules and sanctions might play in controlling groundwater abstraction, the project is looking at ways of conserving the benefits artificial recharge activities bring over the longer term.

national consensus on a broad policy framework for water management. The NWP calls for an holistic, integrated and basin-orientated approach to water management, emphasising decentralisation and greater participation in water management decision-making (Joshi, 2001). In terms of watershed development and artificial recharge activities, the publication in 1994 of new Guidelines on Watershed Development (Government of India, 1994) marked a significant shift in approach. The guidelines emphasise the need for participatory, decentralised decision-making, and are intended to put the livelihoods of poorer groups at centre stage (see below).

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[2] 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, 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.

In the section below, we discuss the themes and issues raised above in the context of watershed development in India. A key concern for watershed development – including associated artificial recharge activities - 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). In India, there have been radical changes in policy approach in recent years, with shifts not only in programme objectives, institutional arrangements and the locus of control, but also in lead technical arrangements and preferred ownership and management regime (from exclusive state ownership and access to resources, through state-community partnerships). This evolution reflects changing state priorities, attitudes and strategies for natural resource management.

4.2.1 Evolution of watershed programmes in India

In India, activities aimed at augmenting groundwater resources through artificial recharge generally form part of a wider set of activities aimed at developing, or rehabilitating watersheds. This is certainly the case for government-funded schemes (the majority) that 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-

[2] Stakeholders include communities themselves, as well as NGOs, the private sector, government and development agencies.

watershed development.[3] The micro-watershed concept was aimed at "establish an enabling environment for the integrated use, regulation and treatment of water and land resources of a watershed-based ecosystem to accomplish resource conservation and biomass production objectives." (Jensen et al., 1996).

As the above quotation implies, early watershed development programmes took ecological objectives as their starting point. Ecological objectives have defined the scale and scope of watershed projects, and have been managed as 'public works' with very limited local participation. In this sense, the state led, rather than facilitated, the process of development. Perhaps unsurprisingly, reviews of early projects indicated limited success in meeting environmental and 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 bottom-up and people-centred planning approach. In particular, there was a shift away from ecological targets, to the rehabilitation and development of environmental resources in an integrated manner to develop *economic* resources within the watershed (James and Robinson, 2001). This included recognition that many land-based activities did not help the landless or the poor, and that management of natural resources needed to be linked with support for sustainable livelihoods. 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 institutional arrangements for this state/community partnership approach are summarised in Figure 3 and described below. 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 organisations (PIAs), including NGOs.
- In **decentralising the management of programmes** to local government, where possible, and to PIAs. The guidelines specify that, in states where *Panchayati Raj* institutions[4] (PRIs) have been introduced, *Zilla Parishads* may have overall responsibility for programme planning and implementation; that PRIs should be part of the Watershed Association; and that members of the *Gram Panchayat* should be part of the Watershed Association. Similar involvement is ascribed to the PRIs in terms of financial provisions, the planning process and technical aspects of projects.
- In facilitating the **participation of local people** in the design and implementation of watershed rehabilitation activities, including artificial recharge, through especially appointed Watershed Committees. A Watershed Committee includes members of the elected village assembly (*Gram Panchayat*), as well as members drawn from a district-level (multi-disciplinary) Watershed Development Team.

[3] In India, micro-watersheds are generally defined as falling in the 500-1000 hectare range. A mini-watershed comprises a number of micro-watersheds and covers around 5000 hectares. A macro-watershed is equivalent to a river basin, and may encompass many thousands of hectares (Farrington et al, 1999).

[4] *Panchayati Raj* is a system of democratic governance. In 1993 the system was written into the Constitution as the 73rd Amendment. The Amendment specifies three tiers of local government: the village (*Gram Panchayat* – often several villages); the block (various local names, including *Taluk*); and the district (*Zilla Parishad*). All tiers should be able to function as 'units of self-government'. The XIth Schedule states that *Gram Panchayats* have a mandate to prepare plans for the management of natural resources within their boundaries.

- In allowing **local control over the disbursement of central funds** for rehabilitation, through District Rural Development Agencies (*Zilla Parishads*)

One objective of the guidelines is to achieve convergence in approach between the different ministries and departments implementing watershed-based activities (see below). However, this 'single window' strategy is not yet, to the authors' knowledge, in force. Early experience suggests that the guidelines have helped clarify and guide policy, but that they have not been in force long enough to significantly affect implementation on the ground (Farrington J et al., 1999). Clearly the restructuring of programmes will take time to become operational in both spirit and practice (Turton et al., 1998) (Farrington J et al., 1999). Several key challenges can be identified:

- The **uneven pace of political** reform at local government level hampers decentralisation. The nature and depth of reform of PRIs in the States is a significant factor in determining whether PRIs are able, and willing, to take on responsibilities in watershed management.
- There is ample evidence to suggest that local **user groups tend to be dominated by elites**. This can work to the disadvantage of women and the poor, and especially to the landless who may only benefit indirectly from watershed development through increased labour requirements. An increase in the productivity of private, irrigated land may also lead to an expansion in irrigated area at the expense of common lands used disproportionately by the poor (James and Robinson, 2001).
- There is **political and administrative resistance** to decentralisation, as well as operational inexperience of working with PRIs and PIAs. The retention of key resources, rights and powers of veto inevitably limit the extent to which non-government partners, for example, can influence the state, share lessons or contribute equally towards shared objectives.
- Control over different natural resources within a watershed is still vested in different government departments. Integrated strategies for the development of soil, water, forests, grazing etc may therefore remain difficult to institute operationally on the ground because of **different and sometimes competing mandates**.

Presently, micro-watershed management absorbs over US$500 million per year, channelled mainly from central government sources. The various schemes of watershed-based development each have a slightly different focus in terms of areas covered and activities implemented. Table 2 summarises the various programmes. The principal schemes are the National Watersheds Development Project for Rain-fed Areas (under the Ministry of Agriculture and Cooperation), and the various programmes implemented under the Ministry of Rural Development. The Ministry of Environment and Forests, and the Ministry of Water Resources also implement watershed-based programmes, leading to major coordination problems.[5] Donors have shown considerable interest in watershed development, not least because it offers the potential to put into operation IWRM principles with support for rural livelihoods. However, the funds that donors provide amount to little over 10% of those provided by the Government of India.

[5] Coordination is a major problem within the water sector more generally. There are five different ministries dealing with water in India, and numerous divisions and sub-divisions within the ministries have water management roles and responsibilities. These are replicated at the two lower tiers of water administration: state and local government. Differences in the pace and purpose of structuring of water organisations at the local level, part of the fledgling decentralisation process, adds to the problem (Joshi, 2001).

Table 2 Different watershed based development programmes – Government of India. Source: James and Robinson (2001).

	Drought Prone Area Programmes (DPAP)	Desert Development Programmes (DDP)	Integrated Wastelands Development Projects	National Watershed Development Projects for Rainfed Areas (NWDPRA)
Year of start	1971	1978	1992	1990
Ministry	Rural Development	Rural Development	Rural Development	Rural Development
Cost sharing	75% Central govt. 25% State govt.	75% Central govt. 25% State govt.	100% central govt.	100% central govt.
Objectives	To mitigate the adverse effects of droughts and create additional employment opportunities	To mitigate the adverse effects of droughts and create additional employment opportunities To check further desertification, restore ecological balance and promote economic development	To take up integrated wasteland development based on village/micro-watershed plans	To conserve and develop natural resources and manage them sustainably. To enhance agricultural productivity & production in a sustainable manner. To restore ecological balance in a degraded and fragile rain-fed ecosystems. To reduce disparity between irrigated and rain-fed areas. To create sustained employment opportunities for rural communities.
Activities	Land development and soil-moisture conservation through measures like terracing, bunding, vegetative barriers etc.	Land development and soil-moisture conservation through measures like terracing, bunding, vegetative barriers	Land development and soil-moisture conservation through measures like terracing, bunding, vegetative barriers etc.	
	Drainage line treatment through vegetative engineering structures	Stabilisation of shifting sand dunes, shelterbelt plantations, wind breaks	Drainage line treatment through vegetative and engineering structures	
	Water resource development through water harvesting structures	Water resource development through water harvesting structures (khadins, tanks, etc.)	Water resource development through water harvesting structures	
	Afforestation and pasture development	Afforestation and pasture development	Afforestation and pasture development	
	Agro-forestry, horticulture and silvipasture	Agro-forestry, horticulture and silvipasture	Agro-forestry, horticulture and silvipasture	
Cost	Rs. 4,000-5,000 per hectare for 500 hectare watersheds = Rs. 20-25 lakhs	Rs. 4,000-5,000 per hectare for 500 hectare watersheds = Rs. 20-25 lakhs	Rs. 4,000-5,000 per hectare for 500 hectare watersheds = Rs. 20-25 lakhs	Rs. 4,000-5,000 per hectare for 500 hectare watersheds = Rs. 22.50-30 lakhs
Time Period	4-5 years	4-5 years	4-5 years	
PIA	GOs or NGOs, given 10-12 contiguous watershed projects	GOs or NGOs, given 10-12 contiguous watershed projects	GOs or NGOs, given 10-12 contiguous watershed projects	

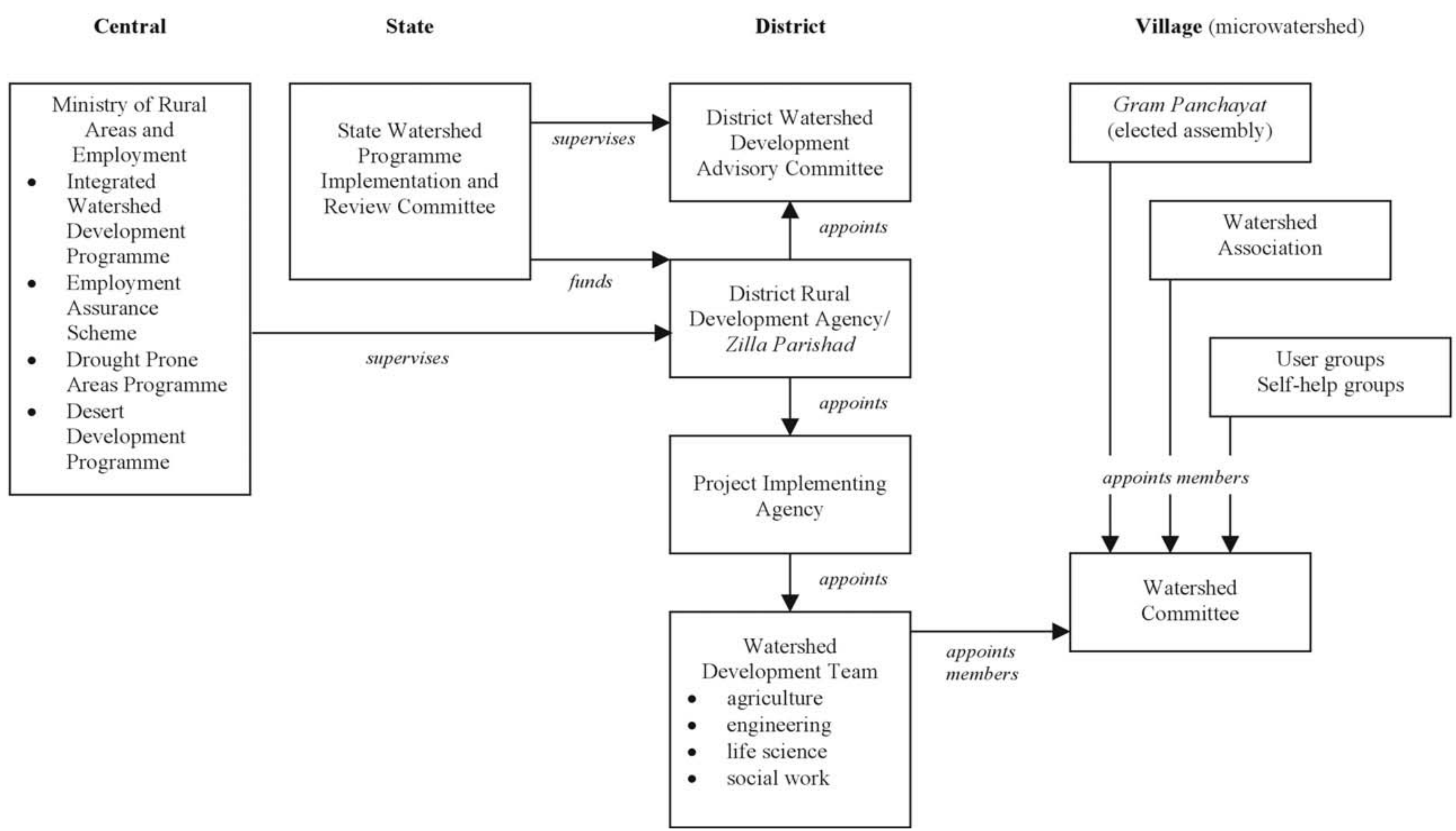

Figure 3 Administrative hierarchy for watershed development projects under the New Guidelines. Source: Farrington et al (1999).

4.3 EVALUATION APPROACH

In this section we describe in broad terms an approach for evaluating the impacts of artificial recharge activities. A key challenge is to trace through the impacts of artificial recharge on local hydrogeological systems, to impacts on the productivity of natural resources, and finally to impacts on livelihoods. The focus on livelihood outcomes is strongly emphasised, as 'traditional' project evaluation approaches have tended to ignore this final link.

The 'success' of artificial recharge activities should be defined in terms of benefits to people – supporting and strengthening rural livelihoods – and in terms of benefits to the environment. People, livelihoods and environmental values, rather than the water resources themselves, are the primary concern. This said, such benefits are only likely where artificial recharge activities do result in some change in the availability and/or accessibility of water resources. As a result, it is important to evaluate both the climatic, hydrogeological, topographic and land use controls that will influence impacts on soil moisture and groundwater conditions, and the household and community characteristics (including the nature, level and distribution of assets, and types of livelihood strategies followed) that will influence who is able to participate in artificial recharge activities, and the nature, level and distribution of costs and benefits.

In order to evaluate impacts, several approaches are possible. One approach would be to first identify those changes in the status of water resources (depth to water table; availability during more months each year; reserve supplies during droughts; increased soil moisture storage; etc) that are directly attributable to artificial recharge activities, and then trace out livelihood impacts. Comparisons could be made with adjacent areas (e.g. watersheds) where artificial recharge activities have not taken place. An alternative or complementary approach would be to work backwards: ask local users what benefits they see from artificial recharge activities and then (a) document whether or not artificial recharge is actually producing the perceived effects on the resource; and (b) assess and document the benefits. Whatever the approach, it is important to recognise the potential for multiple impacts, both direct and more diffuse. For example, field bunds may increase crop yields on a farmer's land, but may also increase the quality of grazing on surrounding common land, with positive effects on milk production, firewood availability and soil stability. The combined impact of artificial recharge activities may, in turn, influence broader livelihood strategies and patterns of migration. At the same time, it is also important to note the potential for negative effects: artificial recharge activities may widen existing inequalities if benefits are captured by wealthier land owning elites; people living downstream may be adversely affected if upstream rivers and streams are blocked; and the presence of stagnant water behind artificial recharge structures may increase malaria risk in some areas.

The discussion above highlights a need to think holistically about the 'effectiveness' of artificial recharge activities. Applying a livelihoods approach can help by explicitly relating artificial recharge activities to livelihood outcomes, including (but not limited to) an analysis of resource impacts. This means focusing on people and their priorities and views on changes. This, in turn, suggests a need for local participation in any evaluation of AR, including the definition, monitoring and assessment of impact. The community may identify some impact indicators, for example, that were not planned or expected (e.g. impact on wildlife; land prices; numbers of children attending school). This type of open-ended enquiry process will not necessarily help identify 'the best' type of scheme, or generic (context-wide) sets of 'success' indicators, as locally defined concerns, priorities and indicators of success may vary from place to place.

Adopting a livelihoods approach may also be useful in informing the wider context in which artificial recharge schemes are conceived and implemented, for example in defining/sharpening activities and objectives, and revising definitions of priority stakeholder groups. Also, in standing back and exploring how schemes affect livelihoods and whether they are addressing locally perceived needs, there is an opportunity to think about how positive outcomes might be enhanced. Examples might include linking and sequencing artificial recharge initiatives with other activities, such as credit schemes and agricultural extension.

4.3.1 Evaluation checklist

A good way to begin thinking about livelihood impacts is with simple checklists. As noted above, it is important to be open-minded about what the potential impacts on livelihoods might be, avoiding the temptation to make early judgements about what is important and therefore what should be investigated.

The checklist below classifies potential impacts into four (overlapping) categories: (1) production and income; (2) vulnerability; (3) water and food security; and (4) social change. Cross-cutting issues, such as distributional and equity concerns, are then discussed briefly below. The list is clearly not the 'final say' on what the impacts of artificial recharge activities may be in different physical and socio-economic settings. Rather, the intention is to generate discussion between project partners on AR-livelihood linkages as a basis for developing indicator sets and designing field surveys in the case study areas.

PRODUCTION AND INCOME

To explore whether (and how) changes in water resource availability and access have affected people's production and income, and how these effects are distributed between different social groups (e.g. land holders vs. wage labourers) and areas (e.g. upstream – downstream):

- Production: levels; types; changes; distribution between different groups and areas
- Sources and levels of income: preservation of existing sources and/or generation of new income
- Changes in percentages from different sources (e.g. farm vs. off-farm; external dependencies (e.g. remittances, aid); marketed vs. non-marketed production
- Income variability/reliability: short, medium and longer-term changes in subsistence and cash income; links with artificial recharge vs. influence of external environmental changes
- Long term investment in assets: how long is people's outlook? Has this changed? What types of assets are people investing in (e.g. land; technology; infrastructure; education; health)

VULNERABILITY

To explore whether (and how) changes in water resource availability and access have affected people's ability to deal with risk – both natural (e.g. drought; floods) and financial/economic (e.g. crop input and output price fluctuations) – and the extent to which different groups have benefited/ suffered in terms of their exposure:

- Vulnerability to drought: e.g. impacts on consumptive and productive uses of water between good and bad years (e.g. wells stay full even in drought years?)
- Seasonality: impacts on consumptive and productive uses of water across seasons (e.g. wells no longer fail in dry season?)

- Flooding: more or less? Who is affected? Who has benefited, e.g. through reduced monsoon flood damage? What were/are the nature of flood damages?
- Coping strategies: what were/are they (e.g. income diversification)? Evidence of change (e.g. fewer sales of productive assets in bad years – distress sales)
- Planning/investment horizons
- Diversification of income sources

WATER AND FOOD SECURITY

To explore whether (and how) changes in water resource availability and access have affected food and water security, and the links between them (strong links with vulnerability above):

- Consumption levels and sources; dietary changes
- Consumption patterns – cyclical vs. longer term changes. Stability?
- Balance between food production for own (subsistence) needs and cash income for food purchase
- Level of food stores across the year
- Links between food and water security e.g. through reduced time to collect water; water availability for productive, income generating uses such as livestock production, cottage industries etc
- Quality of water sources used (e.g. well no longer dries up therefore no need to use unprotected sources)

SOCIAL CHANGE

To explore whether (and how) changes in water resource availability and access have affected household and community behaviour and decision-making:

- Changes in ability/willingness to participate in decision making relating to AR, and in wider forums (civic activity generally). Group 'memberships'?
- Changes in ability/power of people to engage with/make demands on wider policy/government e.g. challenging what the authorities allow/permit
- Social standing of different groups? (this aspect may be a very high priority)
- Views on process, costs, benefits, impacts of artificial recharge across different social groups; participants vs. non-participants; upstream - downstream conflicts etc.
- Sense of control, inclusion and self-esteem
- Expectations: explore whether expectations frustrated, met, exceeded etc. Intended and unintended impacts?
- Labour: patterns of use across seasons and impact of changes in availability; migration patterns (short term and longer term); ability of different households to command labour beyond own direct contribution
- Access rights to resources (nature; changes e.g. to traditional, customary rights)
- Evidence of conflict/cooperation

4.3.2 Cross-cutting issues

It is important to think about where the kinds of impacts identified above ‘fit’ in terms of the priorities of different stakeholders. For example, are the outcomes attributable to artificial recharge schemes a top priority, and do priorities differ between different social groups, areas etc? How ‘positive’ are the choices people are making? For example, is strong involvement in implementation a function of household and community priority, or because funds/support are only available for this particular activity?

Across all of the subheads listed above, it is also important to analyse the distributional and equity aspects of artificial recharge scheme implementation and outcome. For example, how are broad costs and benefits distributed between social groups (e.g. based on caste); between areas (e.g. upstream-downstream effects); and over time (e.g. who are the short term vs. longer term winners and losers; what can be deduced about the sustainability and trajectory of outcomes). Patterns here are likely to be strongly influenced by differences in access to capital assets (human; social; physical; financial; natural) at the household and community level.

Further issues worth highlighting at this stage include the following:

In those areas/projects where artificial recharge is only one element of a broader based watershed development approach (e.g. in India – see above), disaggregating the impacts of AR on livelihoods from complementary/overlapping activities aimed at reducing soil erosion, rehabilitating common lands, encouraging cottage industries etc will be challenging.

- An important limitation on the evaluations that will be carried out on this project will be the lack of baseline data from the study sites. As noted earlier, a thorough analysis requires an examination of pre and post-project conditions in a watershed or a village, but baseline and monitoring data are rarely available for any watershed project in India (Farrington J et al., 1999). For this reason, it will be important to build up a picture of impact using different approaches and methods, including comparisons between different watersheds; and detailed household-level analysis in villages that have apparently benefited, and those, which have not. This will allow some degree of cross-checking.
- It is also important to recognise that baseline conditions will vary greatly from one context to another. The potential of artificial recharge to enhance livelihoods will therefore depend, to some extent, on ‘external’ variables such as the state of infrastructure and access to markets. For example, even where the productive potential of artificial recharge is high, full benefits may not be realised because a village is isolated from markets.

5 Benefits, constraints and uncertainties

The preceding chapters have described, in some detail, the methodologies that are used to implement Artificial Recharge of aquifers as well as reviewing the effectiveness of the techniques from technical and socio-economic perspectives. This chapter aims to summarise and further discuss the findings of the study including the extensive review of literature and the knowledge gathered from collaborators, particularly through field visits and the workshop held in India.

The benefits of utilising groundwater in developing countries have been clearly demonstrated (Moench, 2001; Tsur, 1990; Tsur, 1993); aquifers providing a store of groundwater which, if utilised and managed effectively, can play a vital role in:

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

Rainwater harvesting and artificial recharge contribute to the maintenance of the above benefits, particularly if practised as part of a wider approach to water resource management that addresses demand and quality dimensions as well as supply aspects.

5.1 BENEFITS OF ARTIFICIAL RECHARGE

In general, the aim of artificial recharge facilities is to augment groundwater resources. If the artificial recharge scheme is effective, a rise in groundwater level, or a reduction in the rate of the decline, should be observed. Baseflow from groundwater storage will ensure that surface water bodies flow for longer periods and, in some locations, seasonal streams may develop perennial flow. Wells and boreholes should be able to provide higher yields in previously lean months and the energy consumption for lifting water will reduce. If artificial recharge schemes contribute to groundwater availability, an increasing vegetative cover could be indicative of additional soil moisture which may result in a reduction in soil erosion and a general improvement in fauna and flora, e.g. influx of migratory birds, wildlife etc.

More specific economic benefits from artificial recharge are often associated with agriculture. Benefits commonly discussed include the potential for increases in the total area under irrigation due to the increased availability of water, or a rise in crop yields per hectare associated with improvements in land productivity or multiple cropping. The starting point in assessing such benefits is to recognize that these are, in most cases, equivalent to the benefits associated with groundwater in general. Artificial recharge either enhances or maintains these general benefits.

Most discussions of the benefits from artificial recharge, such as the above, are derived from analyses in industrialized countries. Benefits in rural sections of less industrialized regions have received relatively less attention. As a result, the discussion below highlights the benefits associated with groundwater in general and artificial recharge in specific under these conditions.

In rural agricultural areas, a strong argument can be made that increasing access to groundwater can contribute substantially to poverty reduction and alleviation. Groundwater extraction is closely correlated to declines in the degree and severity of poverty and the number of people living below the poverty line in many major states in India (Moench, 2001). Where irrigation is concerned, groundwater is more reliable than surface sources and can be used with a much higher level of control. As a result, the overall quality of irrigation service is much higher than for tanks or canal systems (Shah, 1993). This is important because it induces the use of complementary inputs (labour, seed and fertilizer) and reduces the risk of loss (Kahnert and Levine, 1989), (Seckler and Amarasinghe, 1999). Furthermore, as documented over two decades ago, water control alone can bridge the gap between potential and actual yields by about 20% (Herdt and Wickham, 1978). The importance of this should not be underestimated as many crops are highly vulnerable to moisture stress at critical points in plant growth (Perry and Narayanamurthy, 1998). Yields in maize can, for example, be reduced by 60% due to water stress at the flowering stage and similar impacts have also been documented for onions, tomatoes and rice (Meinzen-Dick, 1996); (Seckler and Amarasinghe, 1999). As a result, agricultural yields in groundwater irrigated areas in India are generally one-third to one-half higher than in areas irrigated with water from other sources (Dhawan, 1995). The importance of groundwater is not confined to India. Recent findings from Andalusia in Spain, for example, indicate that irrigated agriculture from groundwater is economically over five times more productive (in terms of pesetas/m^3) and generates more than three times the employment in comparison to agriculture irrigated from surface sources (Hernandez-Mora et al., 2001).

While the ability to increase yields is one important dimension in the poverty alleviation equation, risk reduction is equally important. For farmers, droughts can be catastrophic events forcing the loss or mortgaging of core assets such as land. Marginal farmers who depend on credit to finance agricultural inputs (or even their own food between harvests) are particularly vulnerable. Such farmers are often forced to dispose of virtually everything they own at a fraction of its long-term value to pay creditors and survive when drought hits. This creates a vicious cycle of drought and poverty. Assets accumulated during good years evaporate when crops are lost and farmers stay mired in poverty. Irrigation, particularly irrigation from highly reliable groundwater sources, helps to reduce such risk. An analysis carried out for eleven major states in India for the period 1971-84 reveals, for example, that the degree of instability in irrigated agriculture is less than half of that in unirrigated (Rao et al., 1988). Research in the Negev desert and in California has also documented the substantially higher value of groundwater in comparison to surface sources because of its reliability (Tsur, 1990), (Tsur, 1993). As a result of this reliability, the economic impacts of drought in California during the 1990s were minimal; largely because farmers had access to groundwater and were able to shift away from less reliable surface supplies (Gleick and Nash, 1991). Groundwater access in essence provides insurance that other water-dependent investments will not be lost.

In summary, access to groundwater, from an agricultural perspective, has core benefits with respect to:

- Increased yields;
- Risk reduction and reduced vulnerability to drought or fluctuations in precipitation;
- Increased economic returns;
- Reductions in the variability of income.

In India, the above factors contribute substantially to poverty reduction and the sustainability of rural livelihoods. The benefits of artificial recharge essentially maintain and extend these general benefits associated with groundwater access. Artificial recharge does, however, have additional benefits.

Groundwater overdraft and water level declines have major distributive implications. Water levels are the major factor influencing access by the rural poor to groundwater (Burke and Moench M., 2000). As water levels decline, the rural poor tend to be progressively excluded from access. Affordable groundwater extraction technologies, such as treadle pumps, do not function when water levels decline significantly and ultimately only the wealthy farmers, those able to afford deep wells with submersible pumps and an electricity connection, may be able to maintain access. Given these dynamics, artificial recharge can have major benefits from a distributive equity perspective. Where artificial recharge activities increase groundwater levels they enable progressively less well-off sections of the rural population to access reliable water supplies. As a result, artificial recharge is of particular benefit to vulnerable or marginal populations in rural areas.

The health benefits of reliable access to groundwater, including that sustained by artificial recharge, may also be particularly important in rural portions of developing countries. In many such areas, hand pumps and shallow dug wells represent the primary source of drinking water. These generally contain fewer pathogens than open surface sources. As with shallow wells for irrigation, water level declines have a major impact on the ability of populations to access drinking water through dug wells or hand pumps. Even artificial recharge activities that increase water levels on a localized basis (e.g. through the creation of a local groundwater mound) can ensure that such sources function on a continuous basis. In these cases, the volumes involved may not be large or represent a significant increase in the net availability of water but, on a local scale, can be very important. Major benefits also accrue because the process of infiltration inherently filters water and removes suspended solids, contaminants and pathogens through physical and biological processes.

Infiltration through spreading structures can reduce erosion and removal of soil from watersheds. Where vegetative cover is reduced due to over-grazing, forest removal, over-zealous collection of firewood etc., compounded by extended dry seasons or drought, soil erosion becomes a major concern when intense (monsoon) rainfall events occur. Farmers' main asset, their soil, gradually disappears with consequent reduction, or loss, of sustainable livelihoods. Mitigation of the destructive force of flash floods can be attempted with a range of measures including contour ploughing and the construction of earth dams and other structures along the lines of drainage gullies. These measures attempt to reduce the occurrence of sheet flow and to slow the flow in gullies and ephemeral streams. Small temporary impoundments form and these permit settlement of sediment load and, in some instances, the formation of good agricultural land that is utilizable between flooding events. Not only do these land conservation practices retain soil, but they also delay the flow of water from the watershed and hence increase the opportunity for infiltration and hence recharge of the underlying groundwater body. Understanding the dual benefits of these practices enables optimal management of the system in order to achieve the prime objective: soil conservation, artificial recharge or a combination of the two.

Other types of benefits can include maintenance of water availability in local village wells that can greatly reduce the labour individuals, particularly women, must expend collecting water for domestic uses. This can have ripple effects on everything from time availability for other productive activities to general levels of cleanliness and the overall health status of communities. There is, for example, a growing consensus that the amount of water available for personal and domestic hygiene is as important a determinant of a community's health as the quality of that water (Esrey and Habicht, 1986).

Overall, artificial recharge contributes to the maintenance of the above benefits, particularly if it takes place as part of a wider approach to water management that addresses demand and quality dimensions as well as supply aspects. Artificial recharge structures are largely low technology constructions that can be built and maintained by the communities directly involved in the benefits, with little reliance on external advice or constraints.

5.2 CONSTRAINTS ON THE EFFECTIVENESS OF ARTIFICIAL RECHARGE

A wide variety of constraints may limit the impact of artificial recharge on both groundwater conditions and the benefits communities receive. Understanding these constraints is essential in order to target artificial recharge activities or tailor them to site-specific conditions so that demonstrable benefits accrue. Constraints on the efficacy of artificial recharge fall into two broad categories: technical and socio-economic.

5.2.1 Technical Constraints

Core technical constraints on artificial recharge activities include:

- **Water availability**: This may seem self-evident. Many attempts to 'solve' groundwater overdraft problems through artificial recharge, however, are initiated in areas where rainfall levels are low and most available supplies are already utilized. In this case, artificial recharge activities may capture water that is already being used – in effect reallocating water between users with little, if any, additional benefits. Water harvesting and groundwater storage through artificial recharge in the upper watershed may deprive those in downstream parts of the watershed. However, the impacts need to be viewed holistically as upstream harvesting may reduce soil erosion and other damage, and extend the period of streamflow resulting from additional baseflow contributions.

- **Rainfall frequency, intensity and duration**: In many arid areas, rainfall occurs on an irregular basis in brief, high intensity, events. Under these conditions, it is often impossible to capture flows utilising the relatively small structures or dams commonly constructed for recharge in rural areas. Dams overflow rapidly during brief storms but remain dry for most of the rest of the year. Average levels of precipitation are, from the perspective of recharge, often meaningless. What is important is whether or not the rainfall is distributed in a manner that enables capture and infiltration into aquifers. In these conditions, the design of the capture and recharge structures is key to their effectiveness and benefit.

- **Low Permeability Soil or Aquifer Conditions**: Artificial recharge is often difficult in areas where soils have high clay content or tend to form impermeable crusts. In such situations recharge structures often have high levels of evaporation and may actually result in net losses of water rather than contributing to water availability. This can also be a constraint in situations where low permeability deposits overlie higher permeability aquifers. Recharge under these conditions may require more technically complicated facilities for injecting water directly into the aquifers.

- **Water Quality Constraints**: In water-table situations where poor quality water occurs at shallow depths, the benefits of infiltrating fresh water may be lost through mixing with the native groundwater. However, a sound understanding of the hydraulics of this type of situation may permit the effective management of a 'lens' of good quality water, for example where high levels of fluoride, salinity or nutrients occur. In the vicinity of recharge structures it may be possible to improve the quality of groundwater. In other situations aquifers containing high quality water are inter-bedded with low-quality water bodies. While this type of constraint can be overcome through injection techniques, a good understanding of the hydrogeology and hydraulics is needed to minimise the losses of harvested fresh water through mixing with poor-quality water. The quality of the source water (and its variability) also needs to be taken into account, particularly where direct recharge to large open wells is employed. The benefits of filtration and removal of sediment, pathogens, nutrients and other contaminants through infiltration from ponds are largely lost when direct well injection is used.

- **The balance between recharge and evaporation**: Small reservoirs are often shallow and will have high surface area to volume ratios. This can result in relatively high evaporation losses, which may even exceed the recharge contributions to groundwater. Quantifying and understanding the controls on these fluxes will enable better management of the structures through, for example, deepening the reservoir, instituting more frequent cleaning to increase infiltration, constructing pre-infiltration sedimentation ponds or altering the pattern of use of the water from the surface reservoir. A simple method to help understand the effectiveness of artificial recharge structures, even if it only provides a relative assessment, would therefore be an immensely useful aid to making management decisions.

5.2.2 Socio-economic Constraints

Key constraints in this area include:

- **The ability to generate tangible benefits on a reasonable time scale:** In many cases the benefits of artificial recharge accrue to large areas rather than the local areas actually implementing recharge activities. The amount of water stored could be large without resulting in water level or other changes that are directly observable to those implementing artificial recharge activities. In other cases, the benefits of recharge may only occur gradually over long time periods. In this type of situation, individuals and communities may be reluctant to invest time or efforts in artificial recharge.
- **The ability to relate benefits to the group investing in artificial recharge:** Where aquifers underlie large numbers of individual communities, as is often the case in India, the benefits of recharge can accrue to many more users than just to those implementing the artificial recharge activities. In these cases, the benefits of regional participation need to be used to persuade all communities to get involved.
- **Economics:** Artificial recharge activities may not produce economic benefits that accrue directly to those investing in implementation. This is, for example, the case where increases in water levels reduce energy consumption – but farmers aren't paying for the power they use. Charging for electricity would not only encourage more efficient use of water but would also stimulate wider application of artificial recharge practices.
- **Land and water ownership patterns:** Small, fragmented land holdings often limit the availability of space under private ownership where artificial recharge structures can be constructed. In many areas the only available open space is government land, which may be under the control of numerous different departments. Obtaining permission to implement recharge activities on this type of land is often complex.
- **Incentives:** The assumption underlying most artificial recharge initiatives at the community level is that the community has a direct interest in the sustainability of the water resources on which local agricultural and other economic activities are based. This may not be the case where communities are focused on emerging opportunities in urban or non-agricultural economies. In this situation, farmers often seek to maximize current returns in order to generate income to support education or the development of non-agricultural activities regardless of whether or not resource use patterns are sustainable.
- **Inability to control abstraction**: In many cases recharge may be technically and socially feasible but control over-abstraction will be difficult to achieve. Additional groundwater abstraction for irrigation may occur, leading to exacerbation of declining groundwater levels, rather than addressing the original problem. Although the additional contribution to recharge is being exceeded by abstraction, the recharge reservoirs may still provide a valuable resource for fishing, bathing, livestock watering etc.

5.3 UNCERTAINTIES THAT NEED TO BE ADDRESSED

There has been little systematic evaluation of the effectiveness of artificial recharge in different physical and socio-economic contexts, and benefits are often anecdotal. A balanced and informed perspective on the contribution artificial recharge can make to support livelihoods, in a range of different physical and socio-economic settings, is therefore needed.

The main requirement for developing effective groundwater management approaches, utilizing artificial recharge techniques, is the identification of sets of criteria that can guide individuals, communities, governments, and NGOs in their efforts to identify where artificial recharge is likely to contribute in a substantive manner to the resolution of water problems – and where it is not. Criteria are needed to identify:

1. Physical conditions conducive to effective artificial recharge schemes:
   a. Soil type (infiltration capacity and distribution)
   b. Source of water (rivers, rainfall distribution/intensity, wastewater etc.)
   c. Sub-surface storage capacity (geology, degree of confinement, permeability, groundwater flow and quality etc.)
2. Socio-economic conditions, including:
   a. The demand for additional groundwater from either man or the environment
   b. The economics of artificial recharge
   c. The incentives communities may have for implementing and maintaining artificial recharge activities;
   d. Whether or not artificial recharge is likely to be implemented as part of a wider package of management interventions

Hence, in the context of sustainable groundwater management, it is essential to assess the effectiveness of artificial recharge schemes in terms of their ability to recharge the aquifer and to devise criteria to determine the cost-effectiveness of schemes at a range of scales, from individual structures to watersheds and at a regional level. The societal impacts also need to be assessed in relation to differing management practices and the equity of benefits for existing and planned uses, and users.

The key uncertainties are:

- The hydraulic effectiveness of recharge structures. Simple methods to assess the relative effectiveness in different hydrological settings would lead to better management and use of limited water resources. Because of the many hundreds of thousands of existing structures and those under construction, techniques to measure or monitor their effectiveness or to provide guidelines for optimum management need to be accessible, understandable and acceptable to the communities, NGOs, governments and other bodies involved.
- The impacts of different structural designs and management techniques on the effectiveness of artificial recharge schemes. Topics warranting further investigation include periodic silt removal, wetting/drying cycles, water depth, size and number of structures, pre-settlement ponds etc. A better understanding of the significance of these factors could have a beneficial impact on the use of financial and human resources.
- Impacts on livelihoods.
- To date, AR has been undertaken in the context of drinking water supply and agricultural use in rural areas. The potential benefits, and constraints of water harvesting in urban environments also need to be investigated. In addition to the hydrogeological and other technical issues that apply in rural settings, the impacts of large paved areas and roof-top catchments as well as industrial and urban waste disposal and pollution need to be addressed. Deep foundations of buildings and other underground structures as well as service conduits, including water supply pipes, sewers, electricity and telecommunications all need to be considered when planning artificial recharge in urban areas.

These issues needs to be addressed through systematic assessments of the water balances of artificial recharge schemes in a variety of environments in order to provide guidelines on their effectiveness and sustainability. The importance of different management strategies also needs to be assessed in relation to their impact on livelihoods. Bringing these aspects together will provide sound data and guidelines for future investment and sustainable implementation.

The sets of criteria devised for the effective implementation and management of individual schemes, as well as at watershed and regional scales, need to be developed collaboratively with implementers, funders and policy makers. Guidance materials produced will need to be tailored to the needs of end users and their full involvement is needed to ensure knowledge is effectively and appropriately disseminated and internalised.

5.4 IN CONCLUSION

The AGRAR project has provided an opportunity to review the current state of knowledge and practise of artificial recharge around the world but focussing on low-technology application in rural situations. In addition to technical aspects, the institutional arrangements and the impacts on livelihoods have been considered and discussed. Workshops in India have helped to identify issues that can be addressed to improve current knowledge and practise. Information dissemination through the project web site has linked to involvement in activities being led by IAH-MAR, UNESCO, WHO and UNICEF and has resulted in AGRAR being at the forefront of the groundswell of activity in the area.

Phase 1 of AGRAR has established a strong network of partners from NGOs, government, institutes and universities (mainly in India), who are enthusiastic to work together to improve knowledge of all aspects of Artificial Recharge and its impacts on livelihoods. Developing the knowledge gained into decision-support guidelines on best practise and the dissemination of these guidelines, forms the basis for the proposal for Phase 2 of AGRAR, the ultimate goal being to raise the well-being of the poor through better water resource management.

AGRAR has also established a wider network through the IAH commission on Managing Aquifer Recharge (IAH-MAR), providing access to international organisations, programmes and projects including the sixth International Hydrological Programme (IHP VI) led by UNESCO with linked to WHO activities. These programmes provide a wider perspective on the role of aquifer recharge in sustainable water resources management and wastewater reuse as well as mechanisms for global interaction of practitioners, researchers, and institutions and the dissemination of knowledge.

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