Artificial Recharge

The intentional banking and treating of water in aquifers

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AIM OF LECTURE NOTES

These lecture notes are aimed at university students involved in the fields of hydrogeology, hydrology, water supply engineering and water resource planning and management. The intention is to:

- Create awareness on the role artificial recharge can play in water conservation, storage, treatment and integrated water resource management.
- Provide information on the factors that affect the success of artificial recharge schemes.

It is intended that these notes be made accessible by South African universities and education centres to their students.

ACKNOWLEDGEMENTS

These lecture notes emanate from South Africa's Artificial Recharge Strategy (DWAF, 2007). Part of this strategy is to broaden the knowledge base of those involved in the water sector to include this form of water conservation, treatment and storage. They were developed under the project: Strategy and Guideline Development for National Groundwater Planning Requirements (DWAF Project No WP9390) by the Directorate Water Resources Planning Systems, Department of Water Affairs & Forestry with support from the Water Research Commission. They were written by Dr Ricky Murray of Groundwater Africa with input on water quality aspects from Dr Gideon Tredoux, CSIR and on engineering issues from Mr Phillip Ravenscroft, Maluti GSM.

Referencing these notes

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acronyms

AOC	Assimilable Organic Carbon
AR	Artificial Recharge
ARMS	Artificial Recharge Management and Storage
ASCE	American Society of Civil Engineers
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transfer and Recovery
AWWA	American Water Works Association
BCM	Billion Cubic Metres (1000 000 000 m^3)
CBA	Cost Benefit Analysis
CMA	Catchment Management Agency
CMS	Catchment Management Strategy
CSIR	Council for Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
DBP	Disinfection By-Products
DEADP	Department of Environmental Affairs and Development Planning
DEAT	Department of Environmental Affairs and Tourism
DNDE	Department of National Development and Energy, Australia
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DWAF	Department of Water Affairs and Forestry
EAP	Environmental Assessment Practitioner
EC	Electrical Conductivity
Eh	Oxidation-reduction potential, mV
EIA	Environmental Impact Assessment
ENVES	Environmental Engineering Services
EPA	Environmental Protection Agency (USA)
GIS	Geographical Information System
GRA II	Groundwater Resource Assessment Phase II (DWAF)
HAA	Halo-Acetic Acids
HACCP	Hazard Analysis and Critical Control Point Plan
IDP	Integrated Development Plans
IMIESA	Institution of Municipal Engineering of South Africa
ISP	Internal Strategic Perspective
IWRM	Integrated Water Resource Management
MAR	Mean Annual Runoff
MAR	Managed Aquifer Recharge
MARS	Managed Aquifer Recharge and Storage
MFI	Membrane Filter Index
MHa	Million Hectares
Mm^3	Million cubic metres
NamWater	Namibia Water Corporation (Ltd)
NEMA	National Environmental Management Act (Act 107 of 1998)
NGDB	National Groundwater Data Base
NWA	National Water Act (Act 36 of 1998)
NWCDMS	National Water Conservation and Water Demand Strategy
NWP	National Water Policy (for South Africa)
NWRS	National Water Resource Strategy
SAT	Soil Aquifer Treatment
SWECO	SWECO International (Consulting Company)
TDS	Total Dissolved Solids
THM	Trihalomethanes
TOC	Total Organic Carbon
WB	Water Board
WC	Water Conservation
WDM	Water Demand Management
WMA	Water Management Area
WRC	Water Research Commission
WSA	Water Services Authority
WSDP	Water Services Development Plan
WSI	Water Services Institution
WSP	Water Services Provider
WSPF	Water Services Planning Framework
WUA	Water User Association

1. WHAT IS ARTIFICIAL RECHARGE?

1.1 Types of artificial recharge

A brief overview of terminology and descriptions of the major techniques is provided below (Dillon, 2005). These are represented in Figure 1.

- **Aquifer storage and recovery (ASR)** – injection of water into a borehole for storage and recovery from the same borehole.
- **Aquifer storage transfer and recovery (ASTR)** – injection of water into a borehole for storage and recovery from a different borehole, generally to provide additional water treatment.
- **Bank filtration** – extraction of groundwater from a borehole, well or caisson near or under a river or lake to induce infiltration from the surface water body thereby improving and making more consistent the quality of water recovered.
- **Dune filtration** – infiltration of water from ponds constructed in dunes and extraction from boreholes, wells or ponds at lower elevation for water quality improvement and to balance supply and demand.
- **Infiltration ponds** - ponds constructed usually off-stream where surface water is diverted and allowed to infiltrate (generally through an unsaturated zone) to the underlying unconfined aquifer.
- **Percolation tanks** – a term used in India to describe harvesting of water in storages built in ephemeral streams where water is detained and infiltrates through the base to enhance storage in unconfined aquifers and is extracted down-valley for town water supply or irrigation.
- **Rainwater harvesting** – roof runoff is diverted into a borehole, well or a caisson filled with sand or gravel and allowed to percolate to the water-table where it is collected by pumping from a borehole or well.
- **Soil aquifer treatment (SAT)** – treated sewage effluent, known as reclaimed water, is intermittently infiltrated through infiltration ponds to facilitate nutrient and pathogen removal in passage through the unsaturated zone for recovery by boreholes after residence in the aquifer.
- **Sand dams** – built in ephemeral streams in arid areas on low permeability lithology, these trap sediment when flow occurs, and following successive floods, the sand dam is raised to create an "aquifer" which can be tapped by boreholes in dry seasons.
- **Underground dams** – in ephemeral streams where basement highs constrict flows, a trench is constructed across the streambed keyed to the basement and backfilled with low permeability material to help retain flood flows in saturated alluvium for stock and domestic use.
- **Recharge releases** – dams on ephemeral streams are used to detain flood water and uses may include slow release of water into the streambed downstream to match the capacity for infiltration into underlying aquifers, thereby significantly enhancing recharge.

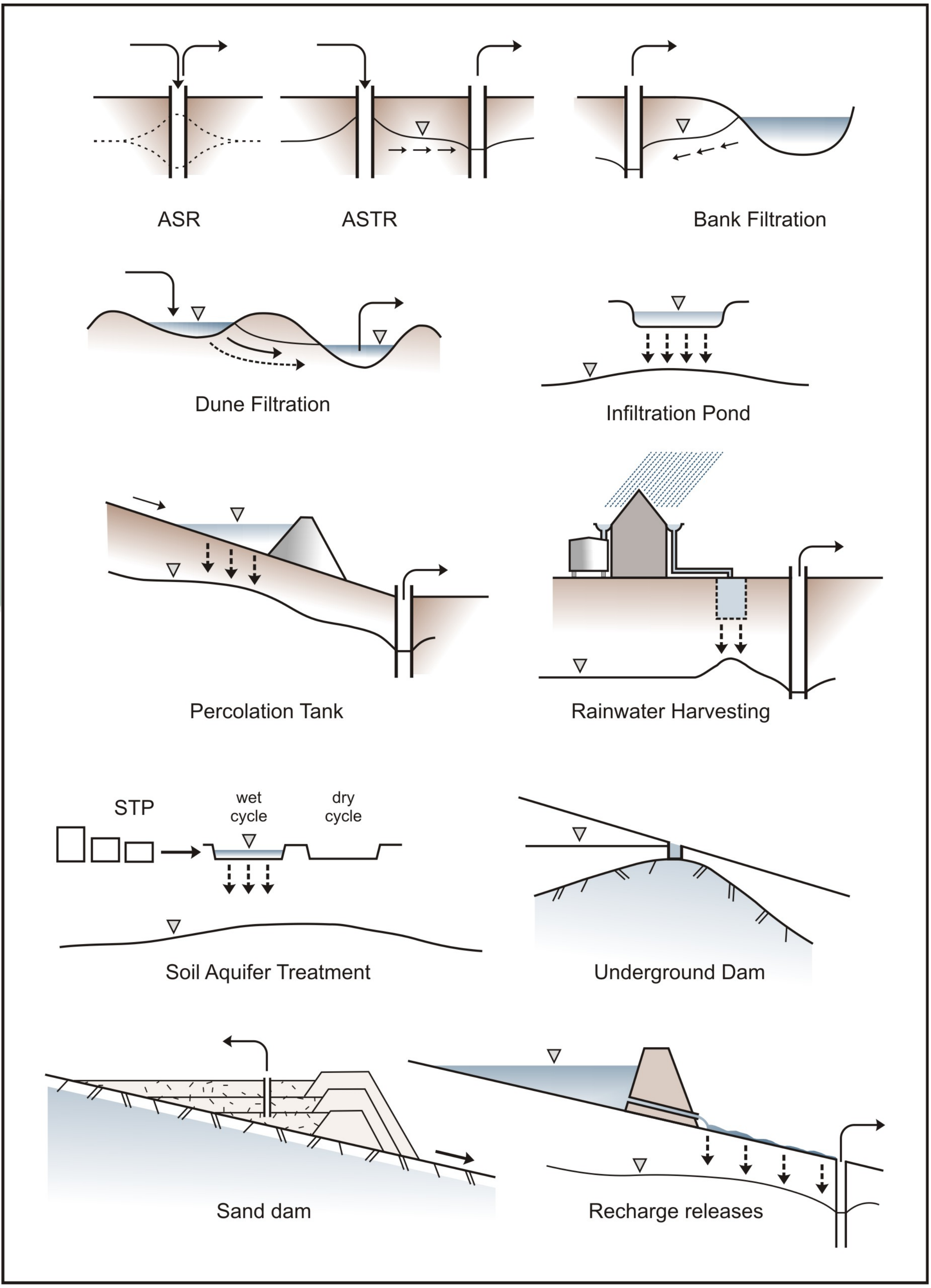

Figure 1: Schematic of types of management of aquifer recharge

(After Dillon, 2005)

Lecture notes

1.2 Aquifer and artificial recharge storage

For the purposes of quantifying groundwater and conceptualising the proportion that should be allocated for use, aquifer storage is divided into dynamic and static components. The dynamic part is that which naturally fluctuates as a result of inflows (natural recharge and lateral inflows) and outflows (discharge as springs, etc). The static part is the deeper and older water that lies below the dynamic component. The question that will need to be addressed in many artificial recharge schemes is what portion of the dynamic and static storage should be allocated for use? Should it only be a proportion of the dynamic storage? If so, the potential benefits may be limited. Or, should it also utilise a proportion of the static storage? In this case, the potential storage will be maximised, but the environmental costs may be prohibitive.

The proportion of aquifer storage available for use in artificial recharge schemes is a management choice based mostly on water volumes, environmental implications and economics.

1.3 Applications, benefits and constraints of artificial recharge

Water stored in the sub-surface can be used to meet domestic, agricultural, industrial and environmental needs. Although sizeable artificial recharge schemes exist that cater for large city and agricultural water supplies, artificial recharge has the advantage over dams in that its economic size can range as low as 1 000 m3/a whereas dams may need to be several orders of magnitude larger to become economic (Dillon, 2005). In arid areas, dams have significant evaporation losses and may allow growth of blue-green algae that produce toxins. Desalination costs are decreasing, but desalination remains a relatively energy-intensive activity and needs a high level of technical support to maintain operations. Table 1 summarises key comparative issues of various water supply sources.

Table 1: Factors affecting technology choice for water supply

Method	Typical scale (m^3/a)	Limits	Relative capital costs	Relative investigation costs	Relative technical. knowledge needed	Relative regulation difficulty
Rainwater tanks	Family $10 – 10^2$	Fails in droughts	*	*	*	*
Springs	Family/village $10^3 – 10^4$	Can fail in droughts	**	*	*	*
Groundwater	Village/town $10^4 – 10^6$	Needs aquifer	***	**	**	**
AR	Village/town $10^3 – 10^6$	Needs aquifer	****	***	***	***
Dam and treatment plant	Region $10^7 – 10^9$	Needs dam site	*****	****	***	***
Desalination	Town/region $10^3 – 10^7$	Needs power and brine discharge	*****	**	****	**

(Adapted from Dillon, 2005)

The applications, benefits, constraints, risks and disadvantages listed below are primarily derived from Pyne (1995), Jones *et al* (1998) and Murray and Tredoux (1998).

1.3.1 *Applications and benefits*

Applications of artificial recharge are summarised in Table 2 and are then briefly described. Depending on the water management goals or the severity of the problem, other water management measures may be required in addition to artificial recharge.

Table 2: Applications and benefits of artificial recharge

Maximise natural storage	Water quality management
• Seasonal storage • Long-term storage ("water banking") • Emergency storage • Diurnal storage	• Water quality improvement • Disinfection by-products (DBPs) reduction • Nutrient reduction in agricultural runoff • Stabilization of aggressive water by storage in calcium carbonate aquifers
Physical management of the aquifer	**Ecological benefits**
• Restoration of groundwater levels • Reduction of land subsidence • Prevention of saltwater intrusion • Enhancement of wellfield production • Hydraulic control of contaminant plumes	• Reduce abstraction from rivers • Maintain the Reserve (maintain groundwater levels and in-stream flow requirements) • Minor environmental imprint • Minimal land use • Temperature control (e.g. for industry)
Management of water distribution systems	**Other benefits**
• Maintenance of distribution system flow & pressure • Storage of treated water	• Defer expansion of water facilities • Storage of reclaimed water • Utilise saline aquifers • Storage of huge quantities of water • Rapid implementation and staged development • Low capital cost • Mitigate effects of climate change • Savings on evaporation

1.3.1.1 Maximise natural storage

1) **Seasonal storage.** Water is stored during wet months when it is available and recovered during dry months.
2) **Long-term storage (water banking).** Water is stored during wet years, or during years when new supply, treatment and distribution facilities have spare capacity, and is recovered during dry years, or when the capacity of existing treatment facilities is inadequate to meet the demand. Water banking not only provides security against droughts, but it also provides security against uncertainty in future assurances of supply due to climate change.
3) **Emergency storage.** Water is stored locally to provide an emergency supply or strategic reserve when the primary source of supply is unavailable. This is appropriate for systems that rely on a single source and a long transmission pipeline.
4) **Diurnal storage.** Where daytime demands exceed supply capacity, night-time local storage is an option (similar to the operation of some hydroelectric plants).

1.3.1.2 Water quality management

1) **Improve water quality.** Certain artificial recharge schemes are designed specifically to improve water quality (e.g. soil aquifer treatment schemes and bank filtration schemes). In such cases and in schemes where the primary goal is storage, improvements in water quality can be significant. Examples include the reduction of nitrate, iron, manganese, hydrogen sulphide, pH stabilisation and softening.
2) **Disinfection by-products reduction.** A drawback of chlorinating water prior to recharge is the formation of carcinogenic disinfection by-products (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAAs). Recent research, however, has shown that DBPs do attenuate during aquifer storage (Gerges, 1996; Toze *et al*, 2001; Pyne, 1998).
3) **Nutrient reduction in agricultural runoff.** Sub-surface storage of agricultural runoff (causing eutrophication of lakes and reservoirs) can reduce nitrogen concentrations through bacterial denitrification. Some aquifers can reduce phosphorus concentrations through physical-chemical and bacteriological mechanisms.
4) **Stabilize aggressive water.** Aggressive water is frequently treated with calcium carbonate. This can be done naturally by storage in suitable limestone aquifers.

1.3.1.3 Physical management of the aquifer

1) **Restore groundwater levels.** Continuing trends in water level decline can be reversed.
2) **Reduce subsidence.** Restoring groundwater levels can reduce land subsidence.
3) **Prevent saltwater intrusion.** Placing recharge facilities between wellfields and the coast or saline aquifers can restrict the movement of the saltwater intrusion front.
4) **Enhance wellfield production.** By enhancing recharge, it is possible to abstract water at higher rates during peak demand months than the long-term sustainable yield of the aquifer.
5) **Hydraulic control of contaminant plumes.** Optimal placing of recharge facilities can create the necessary hydraulic conditions to prevent the migration of contaminant plumes.

1.3.1.4 Ecological benefits

1) **Reduce abstractions from rivers.** Surface water stored in aquifers during wet months would lead to lower stream diversions during the dry months.
2) **Maintain the Reserve.** The Reserve could be supported by maintaining groundwater levels and in-stream, low-flow requirements. For example, river water could be transferred to infiltration trenches parallel to rivers during wet months. The water would slowly return to the rivers thereby enhancing flow during the dry months.
3) **Minor environmental imprint.** Artificial recharge offers a means to store and abstract water with minimal environmental impact. Where confined aquifers are

used (as is the case with many ASR schemes), there is minimal impact on surface water courses.

4) **Minimal land use.** Artificial recharge schemes, and in particular those that employ borehole injection, require relatively small surface areas. For borehole injection schemes, the land use is measured in square metres, whilst the size of equivalent reservoirs would be tens of hectares. For example, a borehole injection scheme extending over a few square metres that stores $1Mm^3$ is equivalent to a surface reservoir of 4 m depth by 500 m by 500 m. The cost, planning, engineering and environmental issues associated with the latter development are of a far greater scale than borehole injection schemes.

5) **Temperature control.** The relatively stable temperatures of the subsurface can be used to maintain water temperatures for industry (e.g. for fish hatcheries).

1.3.1.5 Management of water distribution systems

1) **Maintenance of distribution system flow and pressure.** Optimally located artificial recharge schemes (usually at the ends of long distribution pipelines) can be used to meet seasonal peak demands at maintain adequate pressures in the supply pipelines. They can also be used to maintain a disinfection residual.

2) **Storage of treated water.** Storing treated water allows for the supply of water at a rate greater than the capacity of the treatment plant. This allows for the sizing of water treatment works closer to the average needs rather than the peak requirements.

1.3.1.6 Other benefits

1) **Defer expansion of water facilities.** By optimising conjunctive use of surface and groundwater, and by using artificial recharge principles, expansion of surface water facilities can be deferred, with substantial cost savings. It may be possible to make more efficient use of existing investment in treatment and conveyance capacity by operating these facilities at full capacity throughout the year, and throughout the life of the facility (by incorporating artificial recharge into systems management).

2) **Storage of reclaimed water.** High quality reclaimed water can be stored in fresh or brackish aquifers for reuse. The stored water can be used for a variety of purposes, depending on its quality and post-treatment facilities.

3) **Utilise saline aquifers.** Many ASR schemes utilise saline aquifers that were previously not considered an asset. A fresh water bubble is created around the point of injection, and water quality is managed according to specific targets. The Marathon scheme in Florida, USA, is an example of an ASR scheme where drinking water is stored in a seawater aquifer.

4) **Storage of huge quantities of water.** Aquifers can store huge quantities of water. Table 3 gives an indication of the orders of magnitude depending on aquifer type and extent.

Table 3: Aquifer storage potential

Aquifer type	Aquifer size (thickness x length x breadth)	Storage coefficient	Volume of water stored (Mm^3)
Sand	20 m x 5 km x 5 km	0.1	50
Hard-rock		0.003	1.5
Sand	40 m x 10 km x 10 km	0.1	400
Hard-rock		0.003	12

5) **Rapid implementation and staged development.** Implementation of artificial recharge schemes is generally rapid in comparison with surface water schemes. Borehole injection schemes typically become operational within three years of scheme conceptualisation (Jones, *et al*, 1998). An additional advantage is that it is possible to develop schemes incrementally as the demand arises. Initially, one or two boreholes may be used in ASR or ASTR schemes, with expansion to wellfield scale as required.

6) **Low capital cost.** The **overall** costs of artificial recharge operations are invariably much less than the capital cost of conventional water supply alternatives, especially those involving the development of new reservoirs, treatment facilities or extensive pipelines (National Research Council, 1994; Pyne, 1995).

7) **Mitigate effects of climate change.** Groundwater recharge and storage is expected to decline over the semiarid and arid regions of Southern Africa under currently accepted climate change scenarios (Cave et al, 2003). These changes will require alternative groundwater management practices to control impacts, particularly in situations of groundwater dependency. Artificial recharge may become a useful technology under these conditions.

8) **Savings on evaporation.** Water stored in an aquifer is not subjected to same water losses through evaporation associated with water stored in dams, which can be significant depending on dam location and surface area.

1.3.2 Constraints, risks and disadvantages

It is not possible to implement artificial recharge schemes in all environments. The successful implementation of these schemes is based on a number of criteria that are discussed in Section C. If the necessary assessment of these criteria is undertaken to a sufficient level of confidence, then the risk of scheme failure is small. However, in some cases, the scale (and sometimes, the nature) of the drawbacks only become apparent during operation. In the feasibility stage of artificial recharge projects, most potential drawbacks are, however, identified and an assessment of their severity is made. The ability to deal with the drawbacks usually hinges on economic and management factors.

The drawbacks of implementing artificial recharge usually fall within the following concerns:

1) **Clogging.** Artificial recharge of groundwater generally results in an increased resistance to flow near the point of recharge. This is a result of clogging or plugging, which results in a decreasing rate of recharge or the need to continually increase the recharge head to maintain a constant recharge rate.

Clogging can be caused by physical factors (such as air entrapment and suspended matter), bacteriological factors and chemical factors. Clogging also has a negative impact on the recovery of artificially recharged water, since it increases drawdown during pumping (if the recovery borehole is clogged).

2) **Uncertainty in aquifer hydraulics.** In the case of new artificial recharge schemes that involve deep-seated aquifers or saline aquifers, little will be known about the aquifers' hydraulic properties. This will either mean that intensive research should be conducted on the aquifer prior to implementation, or that an extensive monitoring system is installed, and that the project be commissioned with an acceptable level of risk.

3) **Recovery of stored water.** Where the characteristics and extent of the aquifer are known in sufficient detail, water levels can be managed to prevent losses of recharged water. *Recovery efficiency* is of concern in borehole injection schemes where the quality of the recharge water and the native groundwater are vastly different. In the case of ASR systems, recovery efficiency is defined as the percentage of water volume stored that is subsequently recovered, while meeting a target water quality criterion (Pyne, 1995). The water quality criteria are typically total dissolved solids (TDS), electrical conductivity (EC) or chloride concentration. Most schemes can be developed to 100 percent recovery efficiency, except those in very transmissive, highly saline aquifers which typically reach 70 to 80 percent efficiency (Pyne, 1995).

4) **Controlled recovery by different users.** The concept of whoever stores the water has the right to recover it is generally accepted throughout the world. It would be highly problematic if there was uncontrolled usage of the stored water.

5) **Regulatory constraints.** Storage of water in the sub-surface needs to comply with the country's water and environmental legislation. In certain circumstances, Departmental approval of a scheme may take a long time, or even be prevented, since implementation of new legislation is untested in relation to artificial recharge.

6) **Damage to aquifers.** This concern refers to the negative effects of recharge such as the precipitation of solids, the dissolution of aquifer material and of contaminants such as arsenic. Precipitation has been observed near ASR boreholes, evident as clogging, but has not been observed as widespread aquifer clogging. The dissolution of arsenic has been observed in a number of instances, and needs to be assessed in the feasibility stage of most projects. Aquifer collapse, due to large-scale dewatering during the recovery stage of the artificial recharge cycle, may be a concern for specific aquifer types (such as unconsolidated, unconfined aquifers). Most artificial recharge schemes around the world are in these types of aquifer, but this problem has not been widely observed.

7) **High outlay before feasibility of ASR can be established.** In certain circumstances (e.g. where there is a poor understanding of the hydraulic properties of the aquifer), it may require a high financial outlay in order to establish the feasibility of the scheme. This will need to be compared with the feasibility studies required for other options.

8) **Operational issues.** Lack of experience in South Africa is an obstacle to artificial recharge development.

9) **Environmental concerns relating fluctuating groundwater.** Artificial recharge could result in groundwater levels being raised above and below the norm, and this can have negative environmental consequences such as affecting groundwater level dependant ecosystems, increased aquifer vulnerability to contamination and sinkhole formation in dolomitic aquifers.

2. INTERNATIONAL EXPERIENCE

Artificial recharge (AR) is not a new concept. For centuries, nomads of the Kara Kum Plain desert in Turkmenistan have enhanced recharge by diverting infrequent surface runoff from clay-rich areas to pits dug into porous sandy areas via long trenches. In Europe, artificial recharge schemes have been in operation for over a hundred years. At Mt Gambier in Australia, surface runoff has been diverted into limestone pits and wells for over a hundred years. The scheme is still an integral part of the city's water supply system. A few examples of schemes from around the world are described below.

2.1 ASR in the USA

2.1.1 Introduction

The USA has a long history of both infiltration and injection schemes. Text books, guideline documents, regulations and many case studies have emerged from the USA, particularly over the past two decades. This section focuses on ASR schemes in the USA, of which the oldest, a seasonal storage scheme in New Jersey, has been in operation since 1968. In most cases, the aquifers used for storage are confined, that is, they have a relatively impermeable layer above them, and the ASR boreholes are drilled through this layer into the most porous and permeable parts of the aquifer (Figure 2).

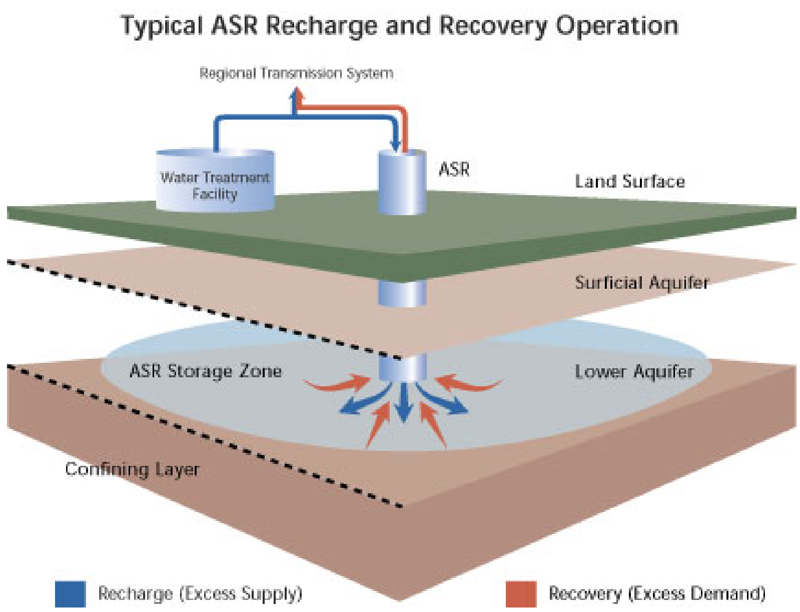

Figure 2: Typical ASR recharge, storage and recovery operation

(Source: www.regionalwater.org)

There has been a noticeable increase in the number of ASR schemes during the past 20 years (Figure 3). A recent survey shows that in 2001, there were 30 operational schemes and a further 10 pilot studies being conducted (AWWA, 2002). Most of the current ASR schemes involve potable water and are designed to increase the efficiency of water system operation.

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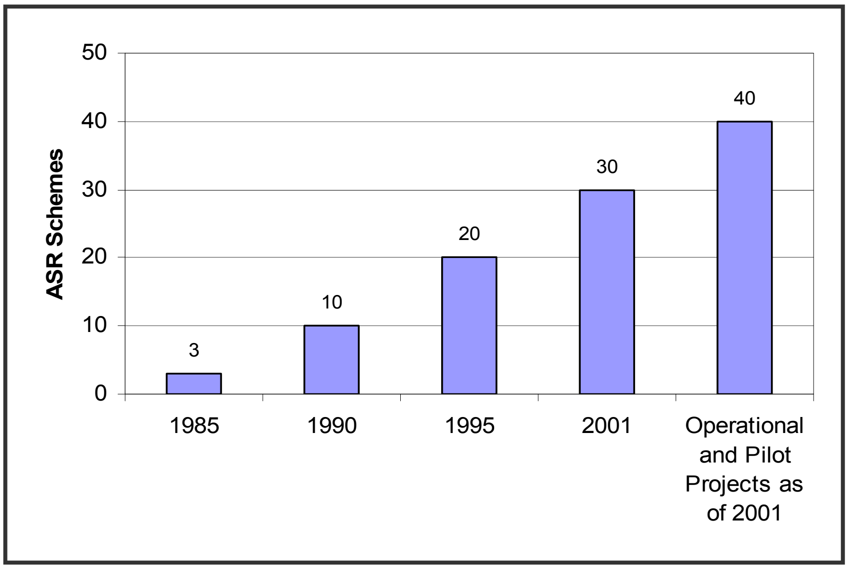

Figure 3: Historical development of ASR schemes in the USA

(Source: AWWA, 2002)

Together with the increase in ASR schemes, there has been a recent shift toward incorporating ASR to meet larger, regional objectives rather than isolated boreholes here and there to meet local needs. Project plans are getting larger, as in the Florida Everglades restoration – 6.4 Mm^3/day with 330 boreholes; New York City – 0.85 Mm^3/day; Calleguas Metropolitan Water District, California - 0.23 Mm^3/day; and San Antonio Water System, Texas – 0.23 Mm^3/day (D. Pyne, *pers comm*). The largest existing ASR operation is in the Las Vegas Valley Water District. This has an ASR recovery capacity of 0.59 Mm^3/day (D. Pyne, *pers comm*).

The American Water Works Association (AWWA) survey shows that most schemes are used primarily for municipal supplies (Figure 4) and for seasonal storage (Figure 5). Many of the schemes have secondary benefits such as the recovery of groundwater levels, prevention of saltwater intrusion, protection of endangered species habitat, improvement of groundwater quality and use of surface water allocations.

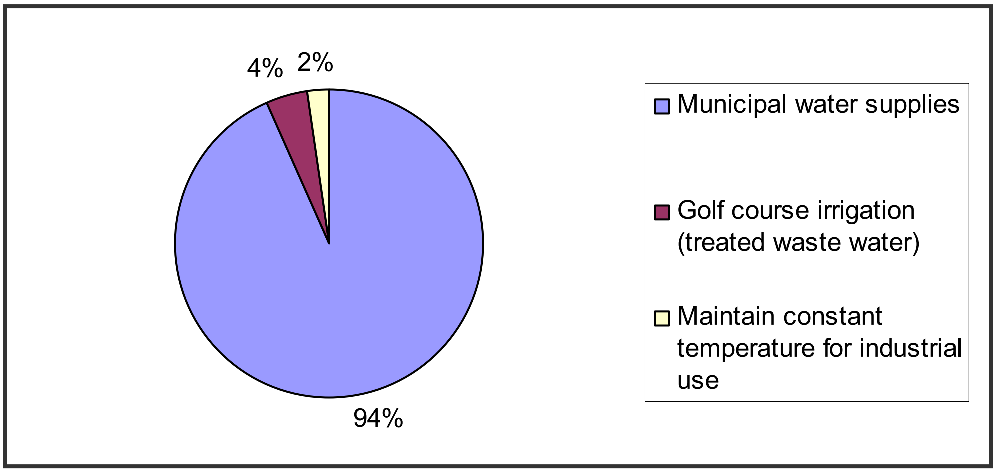

Figure 4: Uses of ASR schemes

(Source: AWWA, 2002)

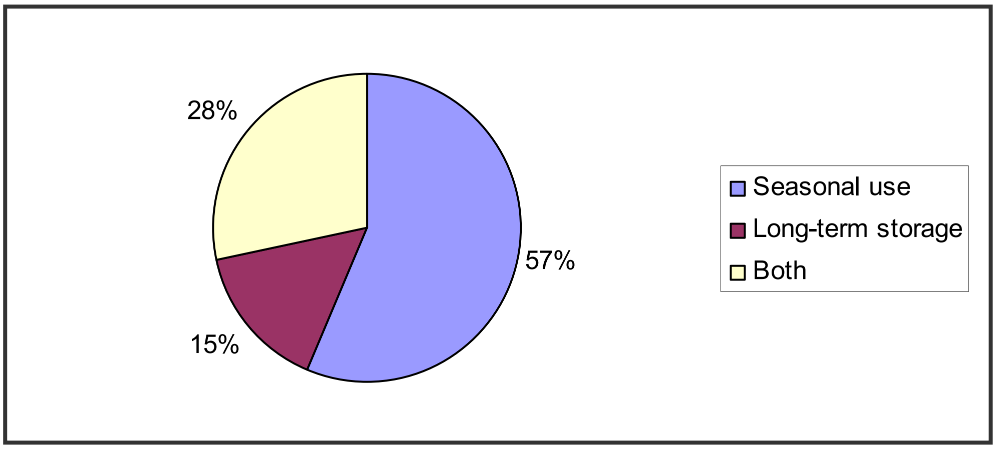

Figure 5: Use of ASR schemes in relation to duration of storage

(Source: AWWA, 2002)

The survey indicated that, in most cases, the water source is surface water (Figure 6). Interestingly, a number of schemes involve transferring groundwater from one aquifer to another. Presumably, this is a form of balancing storage or creating fresh water storage in a saline aquifer.

Of the water sources that have already been treated to meet drinking water standards, only a few are further treated prior to injection (Figure 7).

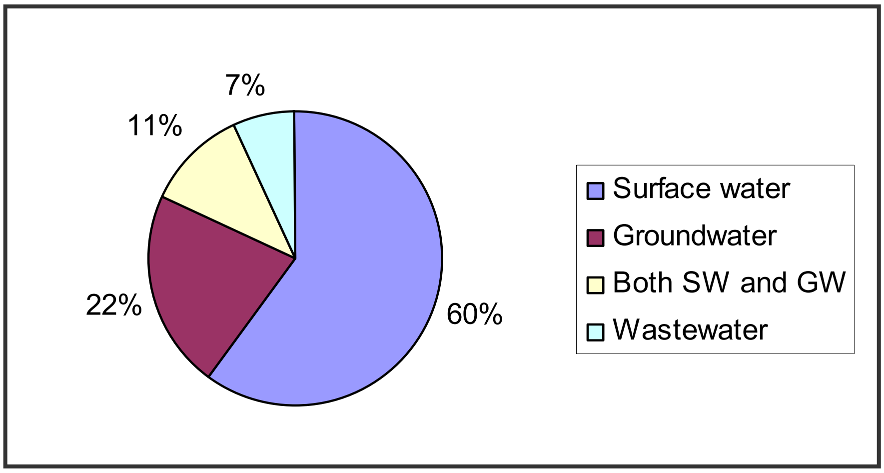

Figure 6: Source water for ASR schemes

(Source: AWWA, 2002)

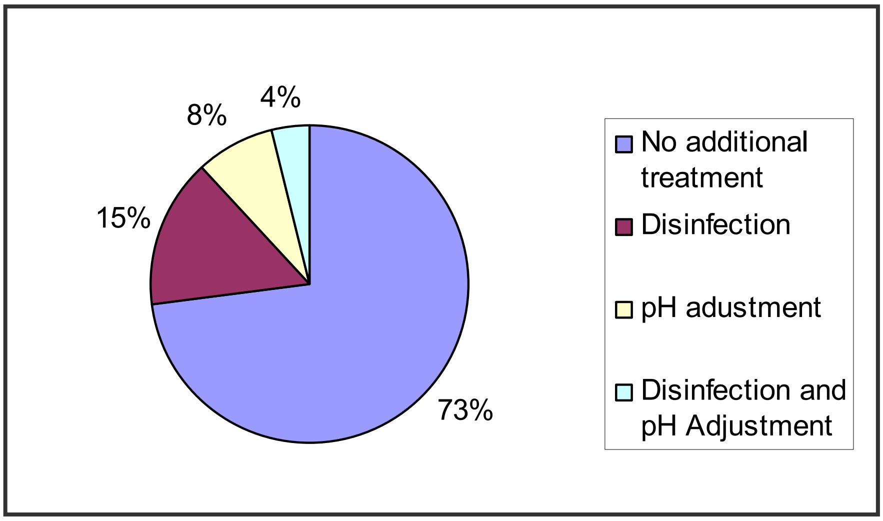

Figure 7: Pre-injection treatment methods at potable water ASR schemes (beyond existing treatment)

(Source: AWWA, 2002)

Most of the potable ASR schemes do not require post-treatment prior to supply (Figure 8).

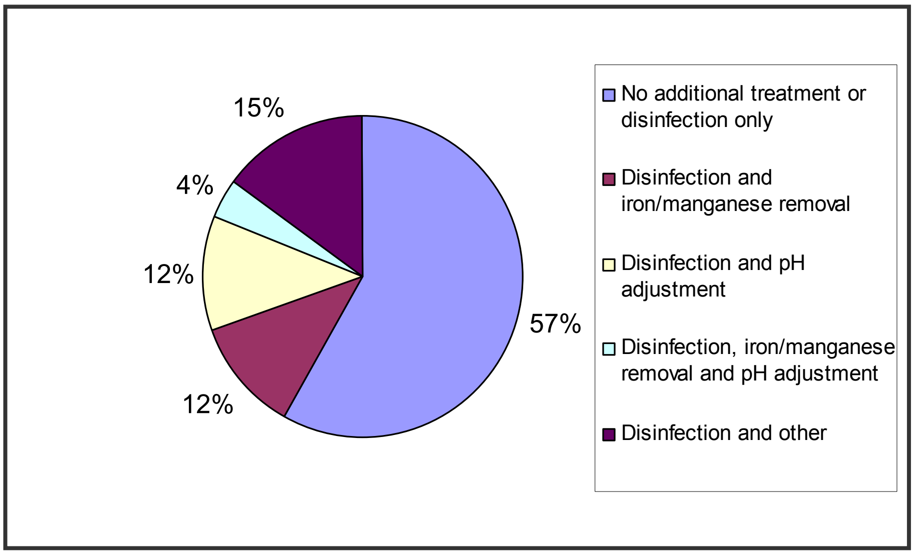

Figure 8: Post-injection treatment methods at potable water ASR schemes

(Source: AWWA, 2002)

Sources of information:

- AWWA, 2002
- www.regionalwater.org

Lecture notes

2.1.2 Peace River, Florida: Large scale ASR in a limestone aquifer

The Peace River ASR scheme is described because it is an example of a large-scale water conservation measure that uses artificial recharge principles and a brackish aquifer. It is in a limestone aquifer with some similarities to the dolomites that are fairly extensive in the Gauteng and North West Provinces. Both its aquifer geochemistry and hydraulic parameters are comparable to some South African dolomitic aquifers, although the Peace River limestones are deep-seated and confined by overlying low-permeability formations. A schematic diagram of the water transmission and storage process is shown in Figure 9 and described in Table 4.

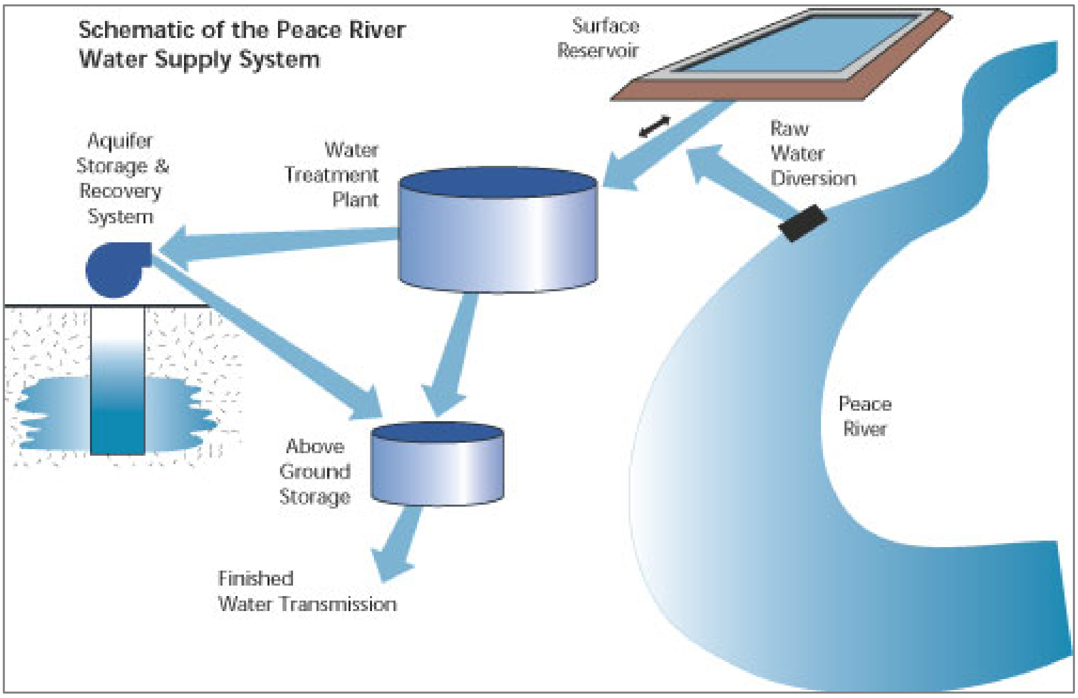

Figure 9: Peace River Water Supply System Model

(Source: www.regionalwater.org)

Table 4: Key features of the Peace River Water Supply System

Scheme	Peace River
Purpose	Primary: Seasonal storage Secondary: Water banking
Aquifer	Two limestone aquifers: Upper: 122 – 152 m deep (30 m thick) Transmissivity: 450 m^2/day; storativity: 0.0004 Lower: 174 – 274 m deep (100 m thick) Transmissivity: 560 m^2/day; storativity: 0.0001
Source water	Peace River. The variable flows and quality mean no diversions are allowed for periods of up to 7 months. Water is stored in the aquifer to cover these periods.
Pre-treatment	Water is treated to domestic standards prior to injection
Water quality	Recharge water (average): Conductivity: 47 mS/m Alkalinity (as $CaCO_3$, mg/L): 50 Groundwater: Conductivity: 122 mS/m Alkalinity (as $CaCO_3$, mg/L): 143
Post treatment	None
Injection/recovery capacity	Injection and recovery capacities per borehole: 2000 – 4000 m^3/day
Injection/recovery history	In the main ASR area, a storage volume of 6 400 Mm^3 has been developed during the past 19 years (81 percent of the target storage volume).
Clogging management	Seasonal back-flushing of boreholes
Recovery efficiency	100%
Implementation stages	1985: 2 ASR boreholes (~6 000 m^3/day) 1988: Additional 4 ASR boreholes (~18 000 m^3/day) 2005: 21 ASR boreholes in total with a combined recovery capacity of 68 000 m^3/day.
Key opportunities and challenges	By deferring or eliminating the need for surface reservoir expansion and relying instead on sub-surface storage, this system is expected to meet regional water demands at less than half the capital cost of other water supply alternatives. Recent elevated arsenic concentrations (in some areas) have led to post treatment, and research into assessing ways of minimising these concentrations. In other areas, the arsenic concentrations have decreased.
Planning process	Planning through the Regional Water Supply Authority has resulted in a comprehensive and phased approach to ensuring the long-term sustainability of water supplies (including the implementation of water conservation measures) and the needs of the environment. A major part of the water supply augmentation plans is to maximise sub-surface storage. The aim is to store excess water during high river flow and withdraw less water from the river during the dry months. By expanding the ASR facilities, they will maximise existing capital investments and enable the Peace River Facility to operate at full capacity.

Sources of information:

- Pyne, 1995
- Pyne, 2005
- www.regionalwater.org

2.1.3 Kerrville, Texas: ASR in a sandstone and conglomerate aquifer

The Kerrville ASR scheme is an effective and financially attractive approach to meeting seasonal and long-term water security needs. Prior to implementing artificial recharge, groundwater levels dropped by 100 m due to over-abstraction from this sandstone and conglomerate aquifer. The hydraulic parameters of the aquifer are comparable with some South African sandstone aquifers, although the Kerrville sandstones have primary porosity, whereas most South African sandstones only have secondary (fracture) porosity.

Table 5: Key features of the Kerrville, Texas, ASR Scheme

Scheme	Kerrville
Purpose	Primary: Seasonal storage Secondary: Water banking
Aquifer	Sandstone and conglomerate aquifers Transmissivity: 90 m^2/day; storativity: 0.0007
Source water	Treated surface water
Pre-treatment	Water is treated to domestic standards prior to injection
Water quality	Groundwater and injectant are of similar quality
Post treatment	None
Injection/recovery capacity	Injection and recovery capacities per borehole: 3000 – 6000 m^3/day
Injection/recovery history	Currently the ASR wellfield has 1.6 Mm^3 in storage, with a peak day combined recovery capacity of about 9 500 m^3/day. System peak day demand is typically about 11 300 m^3/day, so the ASR capacity provides substantial water supply reliability.
Recovery efficiency	N/A (Recovery efficiency percentages are only relevant when the two waters are of different quality; here they are similar)
Implementation stages	The current target storage volume is 5.7 Mm^3 to achieve drought security and to meet the projected 2040 demand. The implementation cost of the scheme to meet this target is ~US $3M, compared with $30M for off-stream reservoir construction.
Planning process	In 2002, the City of Kerrville, Texas adopted the *Kerrville Comprehensive Plan – A Link to the Future* as a statement of the City's vision for the future. As part of meeting the city's long-term water security goals, it has adopted water conservation measures and the expansion of the ASR scheme.

Sources of information:

- AWWA, 2002
- Pyne, 1995
- Pyne, 2005

2.1.4 Main lessons from the USA

Probably the best "judge" of ASR schemes are the operators themselves – the agencies responsible for day-to-day operations and scheme maintenance. Many of these agencies also operate other schemes, including surface water schemes, and they are thus well-placed to have a good perspective of a range of different schemes. Key perceptions, issues and concerns raised by 46 operators in the AWWA ASR survey (AWWA, 2002) are summarised below.

Satisfaction with ASR schemes

One of the 46 respondents stated that his scheme would not use ASR again, as there were geological constraints that had prevented the system from operating as planned. In this case, it is presumed that either the permeability or storage capacity of the aquifer is not suitable for ASR; or that the recovery of the water is problematic due to steep hydraulic gradients or uncertainty in groundwater flow characteristics; or that there are problem constituents in the aquifer such as arsenic. Three respondents had reservations due to cost-benefit ratios and lower than expected pressure heads in the aquifers. The remaining respondents were satisfied, although three respondents stated that they would make changes to how they would develop their systems. Figure 10 shows that 89 percent of ASR operators were satisfied with the ASR schemes.

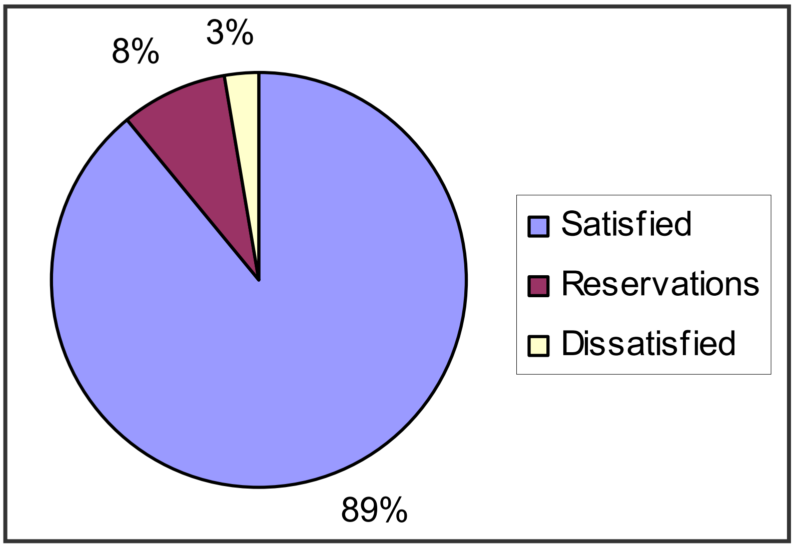

Figure 10: Satisfaction with ASR schemes

(Source: AWWA, 2002)

Benefits of ASR

The benefits relating to the importance of ASR and specifically emphasised by ASR operating agencies are:

- Water conservation and reuse (especially in states that allow treated effluent ASR)
- Recovery of groundwater levels
- Prevention of saltwater intrusion
- Increasing the capacity to meet water demands while minimising impacts on the environment and protected species habitat (particularly in comparison with surface reservoir development)

Challenges

The most common challenges identified are:

- Permitting issues

- Geochemical problems
- Geological constraints (e.g. low permeability, low storage capacity, poorly understood groundwater flow characteristics)
- Water rights issues (ownership of injected water)
- Public relations.

Some agencies reported problems with:

- Clogging (which is more common when the recharge water is not of drinking quality)
- Lower than expected yields.

All these challenges are likely to apply to the South African situation. In many instances, ASR agencies indicated that there would have been value in extending the pilot test stage of the projects (particularly where geochemical problems were anticipated), as this would have affected the design of the schemes, and ultimately made the operation and maintenance more efficient and cost-effective. A key lesson from this is that feasibility studies need to be sufficiently comprehensive to allow a good indication of the viability of the schemes.

Regulatory issues

A key concern causing much frustration among ASR operators is the issue of regulation and permitting. Each state has different regulations, and those states where ASR is being introduced need to develop their own regulations. One Californian ASR facility requires permits from 14 separate agencies for that facility (including the US Environmental Protection Agency and the state Department of Health).

Because artificial recharge is relatively new in South Africa, and because of the new water and environmental legislation, the challenge will be to strike a balance between maintaining the impetus for implementing artificial recharge schemes and meeting water and environmental legal requirements.

Sources of information:

- AWWA, 2002
- Pyne, 1995
- Pyne, 2005

2.2 The Netherlands

Artificial recharge started on a small scale in 1940 with the infiltration of surface water into unconfined aquifers to counteract declining water levels. Large-scale projects were initiated in the 1950s to supply the densely populated areas along the North Sea coast. Groundwater abstraction is restricted in these areas due to salt water intrusion and lowering of the water table.

The volume of artificial recharge water in 1990 was 180 Mm^3 and the withdrawal of recharged water met 22 percent of the country's total water demand. Amsterdam receives 60 percent of its drinking water from artificial recharge in the Dune Area. This artificial recharge scheme involves spreading treated river water over 40 recharge ponds covering 86 ha. The infiltration rates are in the order of 20 cm/day, and travel time in the sub-surface is 90 days on average. The water is recaptured through drains and open canals located about 60 m from the infiltration basins.

Borehole injection is also being used to transfer water to the deeper aquifers. Clogging problems have arisen and a considerable amount of research has gone into the design of boreholes and operational procedures to minimise and manage this problem. The banning of chlorine and similar products for the disinfection of source waters has added to the deep borehole injection and ASR challenge.

- The main purposes of artificial recharge in the Netherlands are:
- To maintain continuity of drinking water supply
- To prevent salt water intrusion after extensive groundwater extraction
- To treat surface water during infiltration
- To reverse ecological damage due to the lowering of groundwater levels.

Sources of information:

- Stuyfzand and Doomen, 2004
- Duijvenbode and Olsthoon, 2002

2.3 Australia

Artificial recharge is not a new concept in Australia. It has been practised for more than a century at Mt Gambier in Southern Australia. This small city disposes all of its stormwater into an underlying karst aquifer using more than 300 drainage wells that are dispersed throughout the city. The annual recharge of between 3.6 and 6.2 Mm^3 makes its way to a nearby lake from where it is abstracted for reuse.

Considerable research into ASR has recently been undertaken in Australia. This has focussed on water quality and microbiological changes that occur due to blending and sub-surface storage. A major part of this research is related to the use of poorer quality water such as stormwater, stream water and reclaimed water. In 2002, 25 ASR projects were in operation, under development or being investigated, with the intention, in most cases, of using storm water and/or reclaimed water for irrigation. Some deterioration of the aquifer due to the injection of non-potable water appears to be acceptable in Australia.

An example of surface infiltration is the Burdekin Delta scheme, which is the oldest and largest infiltration scheme in Australia. The scheme has been operating since the mid 1960s and is largely responsible for supporting the Australian sugarcane area. It is also used to prevent salt water intrusion into the aquifer. The artificial recharge scheme is managed by Water Boards and consists of natural and artificial channels and recharge pits supplied with water drawn from the Burdekin River. The irrigated agricultural land is served by 2 000 production boreholes that are abstracting 210 to 530 Mm^3/a.

Australia is not only implementing innovative ASR schemes but also conducting valuable research. Some of the impressive schemes include those in Adelaide, where urban runoff is diverted to newly-developed wetlands which serve to treat the runoff prior to injection. The water is then abstracted for irrigation purposes in the dry months. In this way, they ensure that the fully treated drinking water is not used for irrigation.

Sources of information:
- Charlesworth, *et al.* 2002
- Gerges, *et al.* 1996

2.4 Germany

Berlin has been supplied with artificial recharge water since 1916; Wiesbaden since 1921; and Hamburg since 1928. Most schemes involve bank filtration along the Rhine, Main, Elbe and Ruhr rivers. Approximately 15 percent of Germany's drinking water is produced through artificial recharge.

The purpose of artificial recharge is mostly for drinking water (54 percent of applications) (Figure 11), but there are also several schemes (less than 2 percent of applications) that are used for the preservation of wetlands, the raising of lake water levels and groundwater rehabilitation.

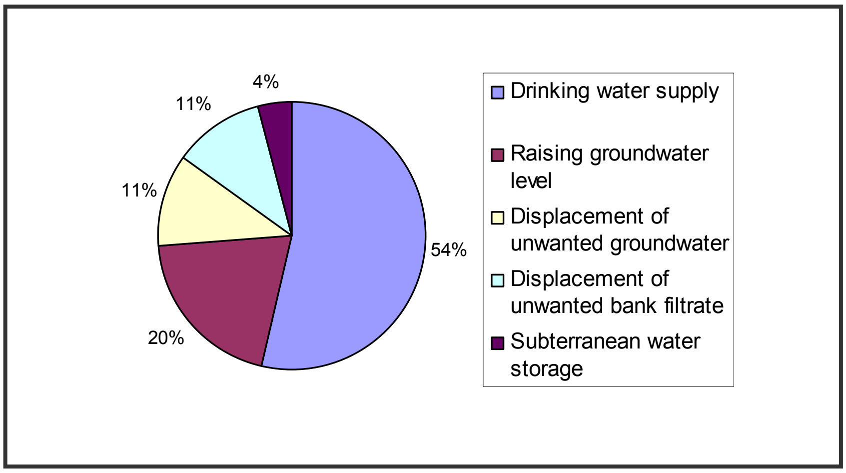

Figure 11: Uses of artificial recharge in Germany

(Source: Schottler, 1996)

Source of information:
- Schottler, 1996

2.5 Israel

Israel has been one of the leading countries in the research and implementation of surface and injection schemes. The Yarkon-Taninim Aquifer, a dolomite-limestone aquifer, is one of Israel's three principal water sources, the others being the Coastal Aquifer and Lake Kinneret. The aquifer is recharged by borehole injection using water from Lake Kinneret. Artificial recharge serves a number of purposes:
- It increases the water reserves for use during the summer months and during other periods of high demand
- It reduces hydrological deficits
- It prevents saline water intrusion from peripheral areas
- It affords efficient utilisation of surplus water from Lake Kinneret.

High volumes of groundwater abstraction caused groundwater levels to drop and, as a result, spring flow was dramatically affected. For example, the Yarkon spring dried up after previously flowing at 220 Mm^3/a, and the flow of the Taninim spring declined from 110 Mm^3/a to 30 Mm^3/a. Artificial recharge volumes have ranged from a maximum of 62 Mm^3/a to a minimum of 4 Mm^3/a, depending on the availability of source water. On average, 26 Mm^3/a, or 7.5 percent over and above the average natural replenishment, was recharged over the 23 year period to 1993. Clogging in recharge boreholes occurs due to silt build-up and algae in the source water, but this is adequately managed by back-flushing (pumping) the injection boreholes.

The largest artificial recharge scheme in Israel is the Dan Region Project that uses the aquifer media for treating reclaimed wastewater from Tel Aviv. The recovered water is used for unrestricted irrigation and over the five year period, 1991 to 1996, a total of 400 Mm^3 was supplied for this purpose.

There are a number of other artificial recharge schemes in Israel, including the Nahaley Menashe project north of Tel Aviv. This is a river runoff scheme where runoff from a three-river system is captured and channelled into a sedimentation basin and then released into recharge basins in the coastal dunes. Similar projects exist in the southern desert area.

Sources of information:
- Guttman, 1995
- Kanarek and Michail, 1996

2.6 Sweden

Infiltration basins have been operational since 1898. There are 1 800 artificial recharge schemes in the country and 80 of the 284 municipalities use this technology. Artificial recharge provides about 50 percent of total groundwater use, which is more than 20 percent of total water use. Recharge is mostly by infiltration basins using partially treated surface water derived from lakes.

Lecture notes

Sources of information:

- Hjort and Ericsson, 1996
- Connorton and McIntosh, 1994

Lecture notes

3. SOUTHERN AFRICAN EXPERIENCE

Artificial recharge is not a new concept in Southern Africa. The Atlantis scheme near Cape Town has been operational for over 20 years, and farmers throughout the region have built numerous earth dams for the purpose of enhancing groundwater recharge. In Namibia, sand storage dams were constructed in stages for the storage of water in artificial "aquifers" (Wipplinger, 1953). Recently, the Water Research Commission (WRC), DWAF and municipalities have supported research and implementation of artificial recharge schemes in fractured aquifers. This initiative this has resulted in two research reports and a booklet (Murray & Tredoux, 1998; Murray & Tredoux, 2002; Murray, 2004). Southern African artificial recharge sites are summarised in Table 6 and Figure 12.

Table 6: Artificial recharge sites in Southern Africa

Site	Operational Status
Atlantis	Over 20 years of operation
Polokwane	Over 20 years of operation
Omdel, Namibia	Over 5 years of operation
Karkams	Over 5 years of operation
Windhoek	Recently constructed
Sand dams, Namibia, etc.	Up to 50 years

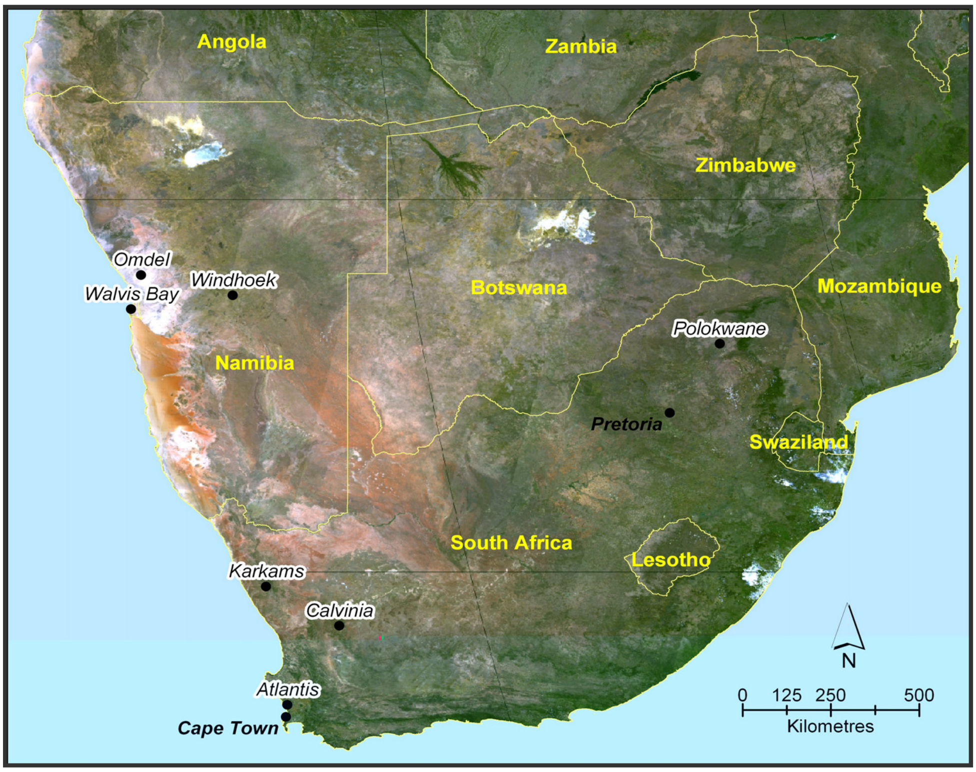

Figure 12: Southern Africa's artificial recharge sites

3.1 Atlantis: Urban stormwater and treated domestic wastewater recharge

The Atlantis Water Resource Management Scheme was designed to optimise the use of water in the town of Atlantis situated along the arid west coast of southern Africa. The town has a population of approximately 245 000. Artificial recharge forms an integral part of the water management scheme.

The stormwater collection and recharge system was constructed in the latter part of the 1970s and it was decided to add treated wastewater from the town of Atlantis to the system. In 1979 it received its first recharge water. At that stage, it resorted under the authority of the Cape Divisional Council but was handed from one local authority to the following until eventually it became part of the Cape Metropolitan area. Since 1997 it resorts under the jurisdiction the City of Cape Town. Initially the system was equipped with various recorders for determining the water level, the rate of inflow into the recharge facility, electrical conductivity and pH. This equipment has been vandalised and is in the process of being replaced. In 1990 the recharge basin was cleaned and the top 250 to 300 mm of soil and sludge removed. The cleaning operation will have to be repeated in the near future and will need attention every 12 to 15 years. Several hundred boreholes and well points were installed for monitoring groundwater levels and water quality. At the first recharge basin some 50 monitoring points were installed and another 30 are located down gradient of the second recharge basin. Groundwater levels were measured monthly or even more frequently in the vicinity of the basins and wellfields.

Figure 13: One of Atlantis' infiltration basins

Refurbishment of all systems is presently taking place and more automated readings are being planned for providing better feedback for operation and management. The City is presently carrying out the water level and water quality monitoring which was previously contracted out and in-house management is gradually evolving. This is important as the City has shown that it is taking ownership of the AWRMS. Further training of staff is required to ensure the success of the operation. The presence of iron has caused clogging of production wells and after several rehabilitation runs detailed monitoring of flow rates and water levels is being introduced for all production wells.

The upgrading of the operation is presently receiving due attention and an operation manual is being planned for supporting the Atlantis staff with decision-making. As various City Departments are responsible for the different components of the AWRMS it needs commitment from all of these to ensure that the wastewater plants are functioning optimally, the stormwater and drainage systems are maintained, the catchment cleaned regularly, while industries are controlled to prevent spillages and pollution. As the recharge system accepts both treated domestic effluent and urban stormwater runoff, these sources need regular monitoring and control. Alternatives exist for diverting substandard treated wastewater and poor quality runoff. However, further upgrading is needed for continuous monitoring of these components. Groundwater quality management is also a key part of the operation as the natural groundwater salinity is relatively high in some areas. Hardness is controlled by partial softening of the water supply. The possibility to introduce low salinity surface water into the system was fully utilised and improved the overall salinity of the water supply. However, surplus surface water will not always be available and therefore the operation of the Atlantis system itself needs to be optimised for controlling salinity levels.

As set out above, the system is presently being refurbished but this task and the associated management present an extensive series of challenges for ensuring product water of optimal quality on a sustainable basis. Presently the scheme runs slightly above half its capacity and the deficit is made up with imported surface water. While this is beneficial for lowering the overall salinity the importation of water is not possible continuously over the longer term and the management of the AWRMS will have to be stepped up to cope with the demands for water quantity and quality.

Table 7: Key features of the Atlantis artificial recharge scheme

Town	ATLANTIS
Population	~245 000
Water demand	6.23×10^6 m^3/a (2004)
Town's water sources	Groundwater (since 1976) and partly surface water (since 2000) In 2004: Groundwater 2.87×10^6 m^3; Surface water 3.36×10^6 m^3 (Wellfields being rested while surface water available)
Water source for AR	Treated waste water and storm runoff. Good quality stormwater and treated domestic wastewater is used to recharge to the wellfields that supply the town. Inferior quality storm runoff and treated industrial wastewater is diverted for recharge near the coast to prevent seawater intrusion (by creating a hydraulic mound near the shoreline).
Purpose of AR	Augment local groundwater supplies. Prevent seawater intrusion into the aquifer. Sensible stormwater and treated wastewater disposal, obviating need for costly marine discharge.
Type of aquifer	Coastal dune sands overlying calcrete and fluvial sand deposits with peat lenses (~45 m thick). Bedrock consisting of shale or granite.

Town	ATLANTIS
Type of AR	Spreading basins: 2 large spreading basins up-gradient of the main wellfield; 3 smaller basins down-gradient near the coast.
First AR activity	1979
Recharge rate/volume	Infiltration rate: 0.01 – 0.16 m/day $1.5x10^6$ to $2.5x10^6$ m^3/a (main basin only)
Recharge rate/volume as percent of current requirement	25 – 40 %
Proportion of water conserved through AR	At least 40 %
Quality of water source	Source for main basins: EC 60 – 95 mS/m; DOC 8 – 10 mg/L Source for coastal basin: EC 100 – 150 mS/m; DOC > 10 mg/L
Quality of water abstracted from the aquifer	Recovered water from main basins: *(blended with groundwater)*: EC 60 – 100 mS/m; DOC 2 – 7 mg/L Recovered water from coastal basin: Not relevant, discharged into the sea via the sub-surface
Comments on the scheme	Artificial recharge has ensured the sustainability of the AWRMS since the early 1980s, and will continue to play a key role. A major component of the scheme has been the separation of the source water into different fractions, as this has allowed recharge of the highest quality water in the areas of greatest importance. The Atlantis groundwater scheme provides a cost-effective water supply option when coupled with careful management of the water sources and the aquifer. Augmentation of the water supply with low salinity surface water since 2000 has decreased salinity and increased the viability of the scheme.
Key lessons	***AR-related:*** 1. Artificial recharge is a reliable hydrogeological proposition when coupled with cautious engineering design and control 2. Water quality monitoring and management remains the key issue for the AWRMS. 3. For optimal artificial recharge implementation, infrastructure planning for urban stormwater runoff and wastewater collection should form part of urban planning design 4. Separation of domestic and industrial wastewater is essential as domestic wastewater can be treated and recycled indirectly 5. Quality of stormwater runoff from industrial areas needs extensive monitoring if used as an artificial recharge source 6. Environmental protection of the recharge zone and general catchment management is needed to maintain water quality 7. Regular and scheme-specific monitoring must be undertaken for effective artificial recharge management 8. Borehole clogging was experienced in both wellfields. Artificial recharge is only practised at Witzand, and thus artificial recharge cannot be the only or main cause of the problem. ***General hydrogeological:*** 1. Production borehole design, construction and materials must be such that borehole rehabilitation can be applied successfully 2. Borehole logging records must be accurate and complete, important for understanding the aquifer and to assist rehabilitation planning 3. Staff training is vital for understanding borehole management for optimum yields 4. Accurate production and monitoring records must be kept 5. Erratic and over-pumping is more likely to promote clogging, while steady pumping at a fixed rate is likely to limit clogging 6. Regular test-pumping of individual boreholes is important to ensure that production yield does not exceed the borehole optimum 7. Pumps and equipment must be carefully selected and regularly maintained.

Sources of information:

- Bishop & Killick, 2002
- Tredoux & Cavé, 2002
- Tredoux, *et al*, 2002

3.2 Polokwane: Wastewater recharge since the 1970s

With a population in excess of 400 000 and water requirements of about 12 million m^3/a, Polokwane is largely dependent on surface water. However, the city also has an elaborate groundwater abstraction infrastructure that supplies domestic water to meet daily peak demand, and serves as a back-up during periods of surface water shortage. For example, during the 1992–1994 drought, groundwater accounted for a large proportion of the city's needs (3.7 Mm^3/a). The reliability of this source is largely due to the infiltration of Polokwane municipal treated wastewater into the alluvial and gneissic aquifers. The water is used both by the municipality and by farmers for large-scale irrigation.

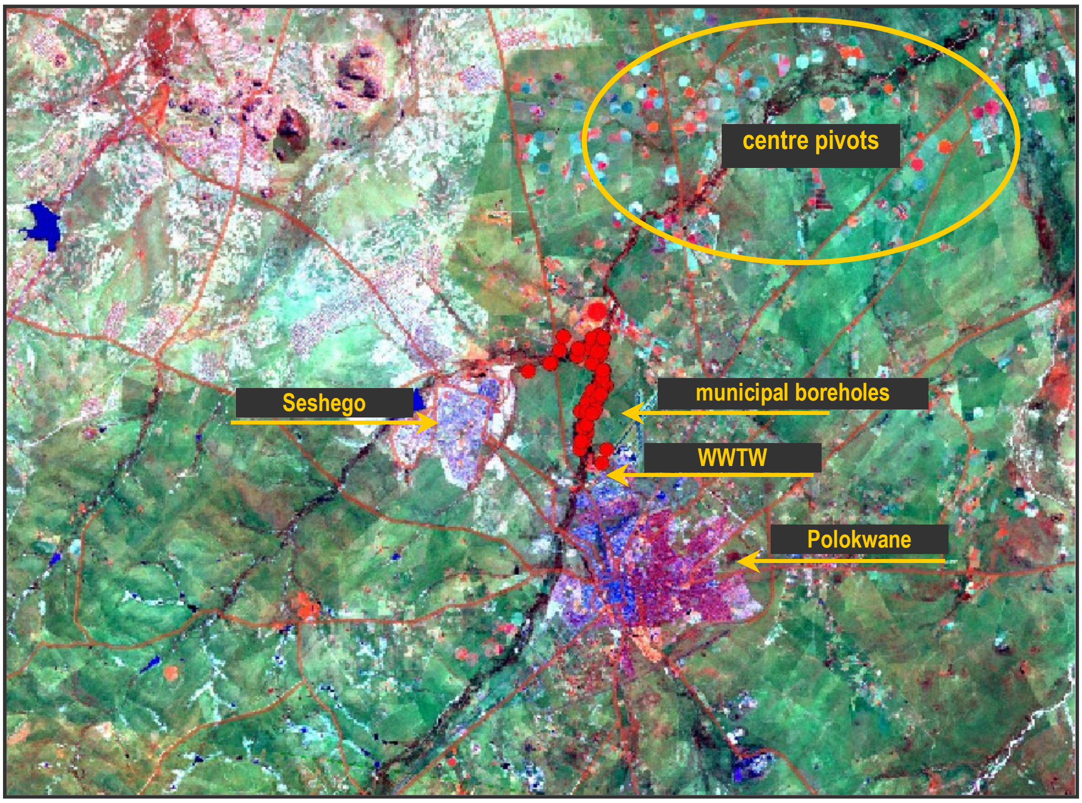

Figure 14: Satellite image showing large-scale centre-pivot irrigation down-stream from the Polokwane Waste Water Treatment Works (This water is abstracted from the hard-rock aquifer that is recharged with waste water)

Lecture notes

Table 8: Key features of the Polokwane wastewater recharge scheme

Town	POLOKWANE
Population	~400 000
Water requirements	12 Mm^3/a
Town's water sources	Surface water; supported by groundwater when needed
Water source for AR	Treated municipal wastewater
Purpose of AR	Artificial recharge was not planned. Recharge to the aquifer takes place as a result of discharging waste water to the ephemeral Polokwane River
Type of aquifer	Sand: ~20 m thick alluvium that absorbs the waste water. Fractured granite/gneiss: ~60 m thick aquifer that is fed by the overlying saturated alluvium
Type of AR	Infiltration into fractured aquifer from river bed and surrounding alluvium
First AR activity	
Recharge rate/volume	Recharge potential: 3-4 million m^3/a (of the 6 million m^3/a discharged by the waste water treatment works)
Recharge rate/volume as percent of current requirement	25-30%
Proportion of water conserved through AR	Conservation potential: 50 - 65% of discharged waste water. So that the municipality can recycle as much of this water as possible, it needs to abstract continuously from the gneissic aquifer. In this way, space is created in the aquifer and the recycling process is made possible.
Quality of water source	Treated waste water: EC: 60-120 mS/m NO_3: <1 – 12 mg/L
Quality of water abstracted from the aquifer	Water from granites/gneisses: EC: 100 mS/m* NO_3: <1 mg/L* * Single sample (Note: There is a lack of historical data to assess discharged nutrients and organics, and the effect of subsurface storage on water quality)
Comments on the scheme	This scheme shows that a large proportion of treated waste water can be stored and recycled using sub-surface media. If this water was not recycled through artificial recharge and subsequent abstraction, it would either be lost to evapotranspiration or it would be pumped from the river or aquifer by other users downstream of the discharge point. When recycled, after abstraction from the deep production boreholes, the water is treated and blended with surface water prior to distribution into the supply network.
Key lessons	1. This form of water conservation is highly effective and is cheap. It should be implemented wherever possible. 2. Because of this scheme, the city has not needed to construct additional surface storage facilities, and can rely on groundwater to meet peak and drought demands. 3. The value of recycling water in this manner can only be realised if groundwater is abstracted from the deep-seated fractured aquifer. If not, the aquifer remains full, and the treated waste water is lost to evaporation, evapotranspiration, or abstracted directly from the river by other users. 4. Additional water quality determinands need to be monitored and analysed for artificial recharge schemes that utilise treated waste water. These should include indicators for potassium, discharged nutrients and organics.

Lecture notes

Source of information:

- Murray and Tredoux, 2002

3.3 Omaruru River Delta (Omdel), Namibia: River runoff

The artificial recharge concept has found great acceptance in Namibia over the past decade, or even longer. The Omdel artificial recharge scheme was constructed in the Omaruru River Delta, in the Namib Desert 35 km from the coast. It consists of the Omdel Dam with a capacity of 40 Mm^3 constructed in 1993, and a series of infiltration basins in the riverbed 6 km down-stream where the present channel crosses paleo river channels (Zeelie, 2002). The main impoundment serves as a silt trap and, after settling, the water is allowed to flow along the river bed to the infiltration basins constructed of alluvial material in the river bed. The aquifer provides water to the coastal towns of Walvis Bay, Swakopmund and Henties Bay, and a large open pit mine at Rössing.

Figure 15: Infiltration basins at Omdel

Lecture notes

Table 9: Key features of the Omdel artificial recharge scheme

Town	WALVIS BAY, SWAKOPMUND, HENTIES BAY, RÖSSING MINE
Water demand	5.5x10^6 Mm^3/a (2002)
Town's water sources	Groundwater from Omaruru River Delta and Kuiseb River alluvium
Water source for AR	Omaruru River floodwater collected in the Omdel Dam (constructed 1993)
Purpose of AR	Recharge to the ephemeral Omaruru River's alluvial aquifer. This water is used for town water supplies
Type of aquifer	Sand and gravel
Type of AR	Direct seepage from Omdel Dam into river alluvium. Seepage into river bed while released water flows to recharge basins. Infiltration of released dam water via recharge basins into alluvial aquifer in paleo channels in river delta
First AR activity	April 1997
Recharge rate/volume	Event driven, 1997-1998, total inflow Omdel Dam: 18x10^{6}m^3 Seepage from dam plus basin recharge: 9.6x10^6 m^3 In 2000: Inflow of 18x10^6 m^3 of which 9.3x10^6 m^3 was recharged
Proportion of water conserved through AR	46 to 48 % of floodwater conserved of total inflow of 18x10^{6}m^3 (subtracting natural recharge in river bed before dam was constructed).
Quality of water source	EC ~57 mS/m in Omdel Dam (1997). EC ~110 mS/m at Recharge Site I (6 km down-stream) (1997)
Quality of water abstracted from the aquifer	EC: ~190 mS/m (average of three production boreholes) (1997)
Comments on the scheme	Flood event driven, but conserves more water by seepage and artificial recharge than would be possible by natural infiltration during flood events
Key lessons	1. A considerable volume of water, which would otherwise be lost as runoff to the sea or evaporation, can be captured and stored in the subsurface where evaporation losses are minimal. 2. The surfaces of the basins need to be scraped from time-to-time in order to maximise infiltration.

Source of information:

- Zeelie, 2002

3.4 Kharkams: Capturing runoff for borehole injection since 1995

Kharkams is a small village in the semi-arid Namaqualand region that depends solely on groundwater. The lowest yielding of the village's three production boreholes is artificially recharged whenever surface runoff is available. This action significantly increases the borehole's yield and water quality. This scheme demonstrates the value of opportunistic artificial recharge in semi-arid areas, even if it is only practised on a small scale.

Figure 16: Sand filter with injection and abstraction borehole (pump house) in the background

Table 10: Key features of Kharkams artificial recharge scheme

Town	KHARKAMS
Population	1 700
Water requirements	80 000 m^3/a
Town's water sources	Groundwater (3 boreholes)
Water source for AR	Ephemeral stream
Purpose of AR	Maximise recharge after rainfall events
Type of aquifer	Fractured granite/gneiss
Type of AR	Borehole injection (1 borehole)
First AR activity	1995 (1st injection run)
Recharge rate/volume	40 m^3/day. Maximum volume injected to date is 6 570 m^3 (2001).
Recharge rate/volume as percent of current requirement	The injection borehole's sustainable yield is 2 400 m^3/a. The injection run of 2001 resulted in a near three times increase in the borehole's annual yield. The daily injection volume amounts to 18% of the town's daily requirements. The volume injected in 2001 was 8% of the town's annual requirements.
Proportion of water conserved through AR	Surface runoff not artificially recharged would otherwise be lost through evaporation and evapotranspiration.
Quality of water source	EC: 20 mS/m
Quality of water abstracted from the aquifer	Without AR: EC: 300 mS/m With AR: EC: 40-100 mS/m
Comments on the scheme	This small-scale, village scheme demonstrates the value of opportunistic artificial recharge in semi-arid areas. Both the borehole's yield and water quality can improve significantly through artificial recharge. If the other two higher yielding boreholes that supply the village were also equipped for injection, then the artificial recharge benefits would be substantial.
Key lessons	Small-scale artificial recharge can substantially improve the quality and quantity of water supplies. Even the most robust artificial recharge systems need maintenance. This may require minimal work, but without basic maintenance, the efficiency of a scheme will drop.

Source of information:

- Murray and Tredoux, 2002

Lecture notes

3.5 Windhoek: Water banking and integrating artificial recharge into bulk supplies

The City of Windhoek has opted for large-scale artificial recharge before introducing other supply options such as transferring water from aquifers in the northern parts of the country and the Okavango River. This decision was based on artificial recharge being the cheapest and most cost-effective option for the city, providing water supply security at accepted assurance levels. These were the conclusions from three recent options analyses and feasibility studies (SWECO, 2002; ENVES, 2003; NamWater, 2004).

The risk of losing injected water is negligible, as the aquifer is bounded by geological formations with low permeability, and the City of Windhoek is the only user of the aquifer.

As part of the NamWater study (2004), modelling was undertaken to optimise the use of water sources that supply water to the Central Areas of Namibia. These results were analysed statistically to provide an indication of required injection and abstraction capacities for the Windhoek Artificial Recharge Scheme. The frequencies of recharge and abstraction were analysed to provide more insight into what can be expected in respect to the reliability of the aquifer. Aquifer storage volumes, as affected by the staged artificial recharge implementation strategy and linked to a range of probabilities of occurrence, are depicted in Figure 17.

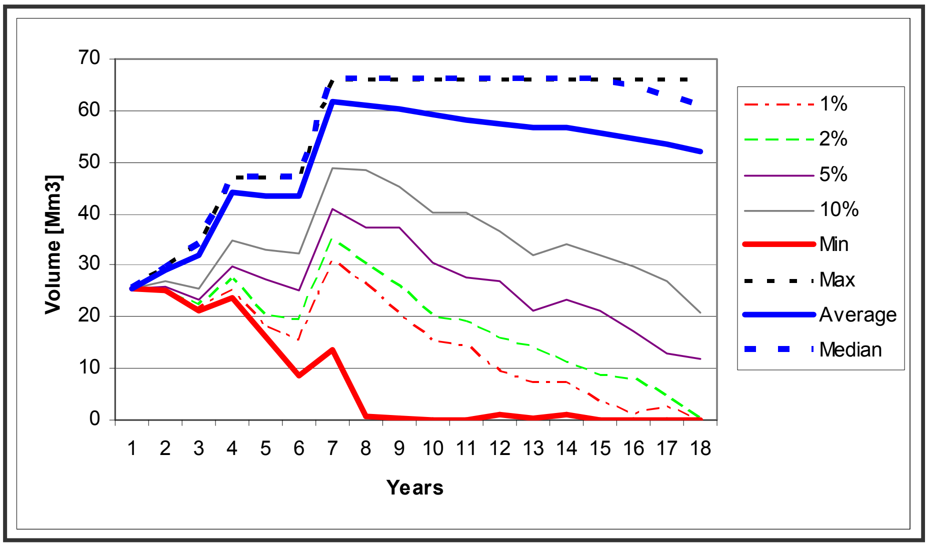

Figure 17: Probabilities of the volume of storage in the aquifer

(Source: NamWater, 2004)

The worst case scenario, with a probability of less than 1 percent, is that the Windhoek Aquifer may be empty by year 8. There is a 5 percent probability that there will be approximately 12 Mm^3 in the aquifer after 18 years and a probability of 50 percent that the aquifer may hold 60 Mm^3 at that time. This equates to three years of the current demand. Water conservation, primarily through savings on evaporation, was calculated to be 13 Mm^3 after the completion of the final implementation stage in year 10 (ENVES, 2003).

A financial Cost Benefit Analysis (CBA) was undertaken for each water augmentation option, based on the expected average water supply over 18 years sold at an assumed bulk water price. The results are presented in Table 11.

Table 11: Results of Financial Cost Benefit Analyses of Augmentation Options

Indicator	Windhoek AR Scheme	Tsumeb & Karst III	Okavango Emergency	Okavango & Windhoek AR
Net Present Value (8%) N$ mil.	-36.59	-95.62	-673.32	-399.59
Internal Rate of Return IRR including inflation	-2.8% 5.0%	-4.0% 3.7%	-4.2% 3.5%	-5.6% 2.0%
Profitability Index (8%)	0.78	0.60	0.17	0.26

(Source: NamWater, 2004)

It is evident from the CBA analysis that none of the options are financially viable, the reasons being that a new scheme will only improve the security of supply and that additional water sales would only be realised during periods of shortfall. Statistically, there is a 55 percent probability that the scheme may not be required to supply any water to the Central Areas of Namibia over the 18-year planning period. The Windhoek Artificial Recharge Scheme has the least negative financial implications, and hence it is the preferred option. The need to go ahead with the scheme is based on a strategic decision that acknowledges the necessity for increased security of supply.

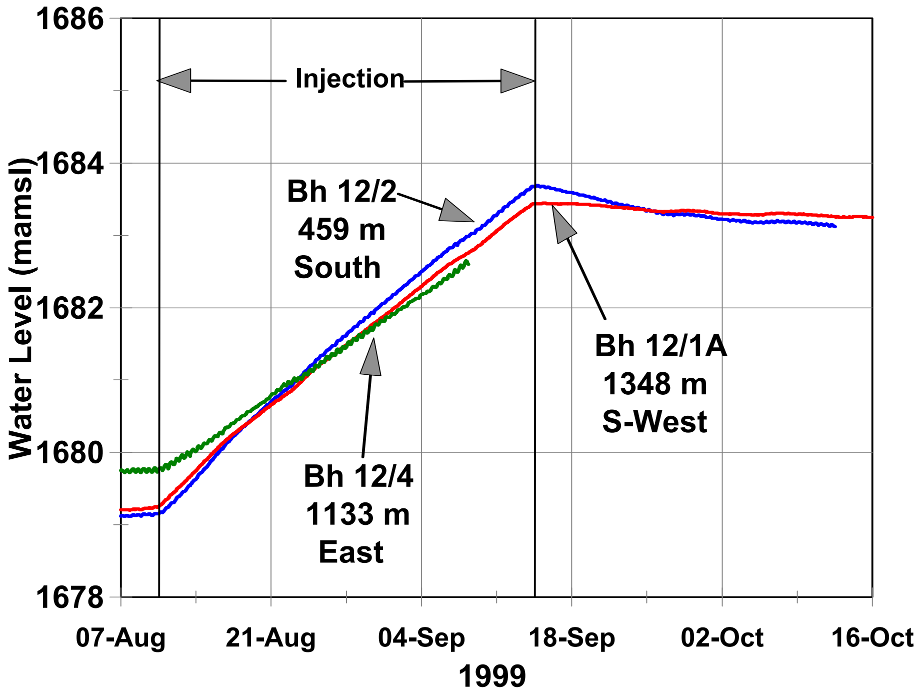

Figure 18: Windhoek, the rise in groundwater level due to borehole injection (Observation borehole number, location and distance from the injection borehole is indicated)

(Source: Murray & Tredoux, 2002)

Table 12: Key features of the Windhoek artificial recharge scheme

Town	WINDHOEK
Population	230 000
Water requirements	20 Mm^3/a
Town's water sources	Dams; groundwater from the Karst area in northern Namibia and the Windhoek aquifer; reclaimed water
Water source for AR	Mainly dam water
Purpose of AR	Water banking to provide security of supply during droughts; seasonal peak demands; and emergency supplies in case of problems with the other bulk supplies or the treatment works (recharged water can be supplied directly into the distribution system without treatment).
Type of aquifer	Fractured quartzite
Type of AR	Borehole injection
First AR activity	1996 – 1st injection test
Recharge rate/volume	Current: 2 Mm^3/a Planned: 8 Mm^3/a
Recharge rate/volume as percent of current requirement	Current: 10% Planned: 40%
Proportion of water conserved through AR	The volume conserved is the evaporation volume saved from the dams; this is difficult to quantify. The value of the scheme lies in the assurance of supply during droughts, seasonal peak demand periods and in emergencies.
Quality of water source	EC: ~50 mS/m Dissolved Organic Carbon (DOC): ~4 mg/L
Quality of water abstracted from the aquifer	Without AR: EC: ~60 mS/m; DOC: <2 mg/L With AR: At this stage, figures are not available, as long-term, large-scale sub-surface storage has not yet taken place. However, since the injectant has better quality than the groundwater, and because the aquifer medium is not highly mineralised, the recovered water should be a good quality blend of the two waters.
Comments on the scheme	The City of Windhoek has opted to implement artificial recharge prior to other options, such as transferring water from the Okavango River. This is because artificial recharge is the most cost-effective option for the city, and it will provide the water supply security needed. It is the first of its kind in the world – large-scale injection in a fractured aquifer, and it should pave the way for similar schemes in highly complex geological settings.
Key lessons	1. Complex, fractured aquifers can be used for AR 2. Detailed hydrogeological assessments are required to understand the groundwater flow system in such aquifers 3. Artificial Recharge can be the most cost-effective option for enhancing a city's water security and supply system.

Sources of information:

- ENVES, 2003
- Murray & Tredoux, 2002
- NamWater, 2004
- SWECO, 2002
- Van der Merwe, B, Tredoux, G, Johansson, P-O, & Jacks, G, 2003

4. CRITERIA FOR SUCCESSFUL IMPLEMENTATION

This section summarises the key factors that the potential for implementing a successful artificial recharge project. It draws on a number of documents and reports, including the Water Research Commission Report entitled, *"Artificial Recharge: A Technology for Sustainable Water Resource Development"* (Murray and Tredoux, 1998).

Since most artificial recharge concerns, and therefore research, revolve around water quality and clogging issues, they are discussed in far greater detail than other issues. Although there are numerous factors that affect the viability of artificial recharge schemes, it appears that, in most international cases, an understanding and an ability to deal with water quality and clogging issues are essential for the successful operation of a scheme.

In South Africa, this is likely to be the same for unconsolidated, sandy aquifers. While both water quality and clogging issues will also be a concern in hard-rock aquifers, the nature of the sub-surface flow will likely be of equal or greater concern. This is because the heterogeneity of fractured aquifers offers the additional complication of "where is the water going to?" and "where will it be best to re-capture it?" Fortunately, a large component of groundwater research in South Africa has been conducted on flow in fractured aquifers, and thus our scientists are well equipped to deal with such issues.

The key issues have been divided into:

1. The need for an artificial recharge scheme
2. The source water
3. Aquifer hydraulics
4. Water quality (including clogging)
5. The artificial recharge method and engineering issues
6. Environmental issues
7. Legal and regulatory issues
8. Economics
9. Management and technical capacity
10. Institutional arrangements

All artificial recharge Pre-feasibility and Feasibility Studies should include information on the above ten "success criteria".

4.1 A clearly defined need

Artificial recharge schemes generally serve a primary need and one or more secondary needs. The objectives of an artificial recharge scheme must be clearly articulated and an approach to assess its success defined, such as defining key performance indicators.

Most schemes throughout the world have been implemented to address a localised water-related problem, for example, water supply for a town or a farming area. This will probably continue to be the case in South Africa; where a localised problem exists, and where both the water source and the aquifer are suitable for artificial recharge. On a regional scale, however, there are areas where both the surface and groundwater resources are nearly fully developed and utilised (e.g. in a number of WMAs in the northern part of the country), and over-exploitation occurs in some localised areas (NWRS, 2004). There is a need to maximise water conservation measures in these areas, and artificial recharge could play an important role where the conditions are favourable for its implementation.

Water supply authorities often think that artificial recharge will solve their problems whereas there may be other measures that could be implemented prior to considering artificial recharge, such as water demand management (WDM), extending existing wellfields or developing new wellfields. Most municipalities in South Africa do not adequately monitor groundwater levels and abstraction, and therefore have little, if any knowledge on how their aquifers are performing. The common statement that "our boreholes run dry" is frequently a statement of mismanagement and an indication that the boreholes are pumped at too high a rates – and not necessarily that the aquifers have been dewatered. That is, the rate at which water can enter boreholes from the aquifer is less than the rate at which they are pumped. By monitoring water levels in both production boreholes and non-production boreholes located away from the pumped boreholes, it would be possible to establish whether aquifers' are indeed stressed, and/or whether borehole pumping rates are too high. Artificial recharge is only required for water supply purposes if aquifers are stressed or have potential to be stressed.

During the artificial recharge pre-feasibility study (described in Section C.2), all existing groundwater level and abstraction data must be assessed, and if there is a lack of such data, then a monitoring programme has to be implemented immediately. At the very least, a full year of groundwater level data is required to establish whether artificial recharge is necessary or not.

Groundwater level data is critical to assess whether artificial recharge is necessary.

As soon as an artificial recharge project is conceived, start monitoring groundwater levels and abstraction; and establish seasonal groundwater and artificial recharge source water quality.

4.2 The quantity and reliability of the source water

The quantity, reliability and quality of a water source determine whether or not it is suitable for artificial recharge. This section discusses quantity and reliability, and the following section address water quality. Recharge water can be obtained from a variety of sources, but mostly from surplus surface water, which cannot be used or reused directly for a variety of reasons, and is lost as outflow to the sea, or through evaporation.

The total available surface water yield (at a 98 percent assurance of supply) for the country is estimated to be 10 240 Mm3/a derived from a natural mean annual runoff (natural river flow) of 49 040 Mm^3/a (NWRS, 2004). There is therefore plenty of water available on a national scale for sub-surface storage. Even in areas such as the northern parts of the country, where the water resources are nearly fully utilised, surplus river water is available (the natural river flow far exceeds the reliable local yield). The suitability for AR will likely relate to the timing of the available water (seasonality) together with other factors such as water quality, ability of the local aquifer to receive the water, etc.

It is important that the water for aquifer recharge purposes is of consistently high quality and has fairly predictable quantity over time. Water quality is covered in the following section. In most artificial recharge schemes, there is a reasonable consistency in supply during the infiltration/injection stage, but in schemes that rely on surface runoff, particularly those in arid and semi-arid areas, reliability is a problem. However, the value of opportunistic artificial recharge can still significantly increase the security of supply.

Table 13 provides a comparison of the quantity, reliability and quality of various water sources. In regards to rivers and dams, quantity and reliability are related to size, existing allocations and geographic location (climatic region).

Table 13: Water sources for AR

Source water	Quantity	Reliability	Quality
Rivers	Variable	Variable	Variable
Dams	Variable	High	Low - High
Treated municipal waste water	Consistent	High	Low - High
Aquifers (i.e. transfers from other sub-surface reservoirs)	Consistent	High	Consistent
Urban runoff	Variable	Moderate - High	Variable
Agricultural return flows	Variable	High	Low
Rainfall harvesting	Variable	Moderate - High	High

4.3 Aquifer hydraulics

Two main physical characteristics determine whether or not an aquifer is suitable for accepting, storing and recovering artificially recharged water. These are the aquifer's hydraulic conductivity and its storage capacity. A third important factor is the aquifer's hydraulic gradient and the natural geological barriers to flow. These relate mostly to the recovery of the recharged water. The key questions are:

- Will the recharge water be able to flow into the aquifer (permeability/hydraulic conductivity)?
- Will the aquifer have sufficient space to accept the water (storage)?
- Will the water be recoverable?

Aquifers which have high hydraulic conductivity and which have high storage capacity are more suitable for receiving additional recharge water than those which have low conductivity and capacity (Figure 19). Highly permeable aquifers, however, are not always ideal for artificial recharge if high quality water is stored in a saline aquifer, as this may result undesirably high blending ratios. Aquifers with high hydraulic conductivity and high hydraulic gradient may also be problematic, as water will flow rapidly away from the point of recharge and may be difficult to recover. This problem is greatest in fractured aquifers and can be averted either by placing recovery boreholes down-gradient of the recharge facility, or by applying ASR principles and reversing the hydraulic gradient during pumping so that water flows back towards the initial point of recharge.

The key issues of storage and hydraulic conductivity are depicted in Figure 19.

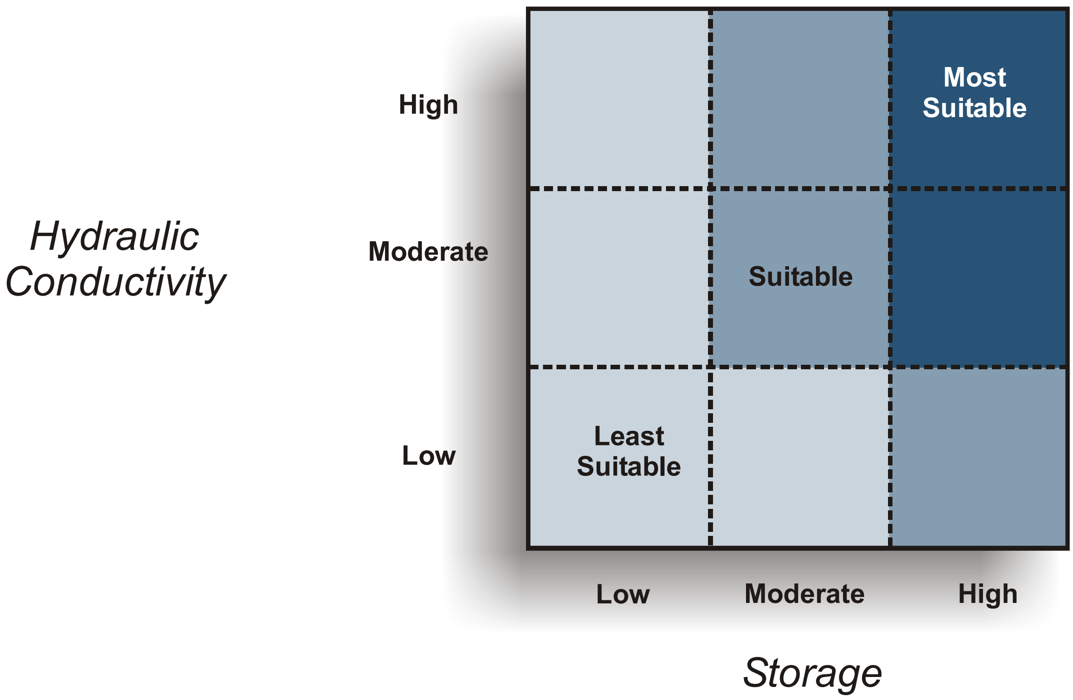

Figure 19: Suitability of an aquifer to receive artificially recharged water (Murray and Tredoux, 1998)

4.3.1 Aquifer geology and geometry

The first step in establishing the hydraulic characteristics of the aquifer is to develop an understanding of its the geological setting. This includes defining which geological formations comprise the aquifer or aquifers targeted for artificial recharge. It requires developing a conceptual flow model for the aquifer based on its geological setting (including its boundaries) and an assessment of the natural recharge and discharge areas.

4.3.2 Storage potential

Unconsolidated, inter-granular aquifers have a greater storage capacity than hard-rock aquifers. Their coefficient of storage, which is related to porosity, is generally one to three orders of magnitude greater. For this reason, alluvial aquifers, coastal sands and the infrequent thick inland sandy deposits are prime targets for the storage of considerable volumes of water. These environments also provide good media for basin recharge and water treatment (SAT).

In South Africa, many aquifers are filled up during the rainfall season. Groundwater levels are commonly within 10 – 20 m of the land surface, and groundwater discharges as springs and seeps. In many areas, the elevated wet-season water levels in rivers, dams and wetlands, are due to overflowing groundwater. Under these conditions, it makes no sense to artificially recharge groundwater. However, artificial recharge creates the opportunity to modify groundwater management practices and to abstract groundwater at rates over and above the naturally sustainable rate – provided that this does not have major environmental or social impacts. The most common impact is caused by lowering the water table, and this can reduce groundwater outflow to areas that previously received a perennial supply (from springs and seeps). It can also cause land subsidence in vulnerable geological environments and boreholes to go dry.

Boxe 1 adapted from DWAF's Groundwater Resource Assessment II Project (DWAF, 2005), provides an overview to the issues related to maximising groundwater use. A key message is that, by applying scientific tools, it is possible to obtain reasonable estimates of sub-surface storage However, in many instances, it remains a management decision, based on prevailing policies, that determines the proportion of the storage volume that can be allocated for use.

Based on particular management criteria, the volume of storage available for use in an artificial recharge scheme will need to be determined. In some cases, where the environmental and social costs are high, it may not be possible to utilise static storage. In other areas, where the environmental and localised social costs are small, and where the broader social needs of having access to water, and the economic gains of having a secure supply outweigh the environmental costs, the allocatable storage may also include the static component.

In Section B.4, a regional scale GIS-based approach is used to assess the artificial recharge potential that includes an assessment of available storage.

Box 1/…

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Box 1 Groundwater use: An issue of science, policy and terminology

The volume of water held in sub-surface storage is variable depending on how full the aquifer is, which is a function of inflows and outflows. The reason for quantifying groundwater is to know how much water on a time basis can be abstracted from a specific area to meet certain requirements. That is, it is time-based, and it is requirements-based. From this definition, the quantity of groundwater that should be pumped over a given period could range from none (the requirement, for example, may be to strive towards pristine conditions) to as much as possible, where the requirement, for example, may be to mine the water as an emergency need whilst another source is being developed for the long-term supply.

This approach takes into account both the procedures of science and guidance of policy. Put simply, science can provide an estimate of how much water is available for use, and policy dictates how much of that must be "left alone" or "used" to meet specific environmental and social requirements.

It is worth noting that there has been considerable debate ever since the first negative effects of large-scale groundwater abstraction were noticed. In 1920, the concept of safe yield was introduced after large-scale abstraction in the western USA was made possible with deep boreholes and electricity-driven turbine pumps. Since then the safe yield concept has been modified and numerous papers have been written on approaches to quantifying groundwater. Some of the terms and concepts that have been developed since the early 1900s are:

- Safe yield
- Sustainable yield
- Groundwater availability
- Exploitation potential
- Abstraction potential
- Harvest potential
- Optimal yield
- Consensus yield.

Added to these terms are those that are commonly used without precise meaning or definition:

- Groundwater overexploitation, over-use, over-extraction and over-development
- Groundwater mining
- Stressed aquifer
- Unsustainable use.

This latter group of terms is used particularly in areas where groundwater is intensively exploited, but the terms are also being used to refer to problems of simple interference between boreholes or mismanagement.

4.3.3 Hydraulic conductivity

Hydraulic conductivity of a soil or rock defines its ability to transmit water. It is dependent on a variety of physical factors, which for sandy aquifers, includes porosity, particle size and distribution, shape of particles, arrangement of particles, etc. In hard rock aquifers, the factors include density, apertures and roughness of the fractures.

For the successful application of infiltration and injection artificial recharge schemes, hydraulic conductivity needs to be sufficient both at the point of recharge and further afield. In hard rock environments, this means that the fractures need to be reasonably extensive and interconnected.

The GIS study in Section B.4 takes hydraulic conductivity indirectly into account by prioritising areas with high yielding boreholes.

4.3.4 Hydraulic gradient and flow directions

The hydraulic gradient determines where the water will flow once it has entered the sub-surface. This is important to know for locating the recovery boreholes. In many cases, it may be possible and cost-effective to recover the water at the point of recharge (eg using ASR boreholes). Depending, for example, on the planned storage residents times, or whether in situ treatment (eg SAT) is needed, it may be preferable to abstract the water down-gradient of the recharge point.

4.4 Water quality

The introduction of artificial recharge generally addresses problems such as the over-exploitation of water resources, saline water intrusion, and a whole series of other issues threatening the continued use of the resource. However, artificial recharge can only succeed if the longer-term sustainability of the practice can be assured. In this respect, experience gained over many decades has demonstrated that the quality of recharge water is the key issue. As a result, extensive pre-treatment of recharge water has been developed for reducing the dependence on purification and blending in the aquifer for quality improvement.

Ecological sustainability issues currently seem to be the most important concern of artificial recharge applications abroad. Pressures are exerted to restore the hydrological systems to their more natural state and to concentrate artificial recharge activities on more confined areas (Olsthoorn & Mosch, 2002). These perspectives need to be taken into account in the development of local artificial recharge schemes, implying that artificial recharge schemes should not overly rely on subsurface water quality improvement but rather be mainly designed for the storage or banking of water. Subsurface storage of water generally adds a safety/protection "barrier" for drinking water supply systems but, where relevant, any water quality improvement in the subsurface should be considered a bonus.

Dillon (2005) sets out a number of objectives for the ASR Code of Practice being developed in Australia. Six of the aims of the primary objective specifically relate to water quality and state the following:

- Protect or improve groundwater quality wherever ASR and ASTR is practised
- Ensure that the quality of the recovered water is fit for its intended use
- Prevent problems such as clogging and excessive recovery of aquifer material
- Ensure that the impacts on surface waters, downstream of ASR and ASTR operations, are acceptable and are taken into account in catchment water management
- Ensure that an appropriate public and environmental health risk assessment and management strategy is in place to deal with potential variations in water quality of injectant.

These objectives are generally valid for all artificial recharge schemes and these form the basis for the water quality aspects discussed below.

4.4.1 Quality of groundwater

One of the objectives of artificial recharge is to protect or improve groundwater quality. In the majority of cases where groundwater is utilised as a potable supply, or for stock-watering, irrigation or other purposes, the objective would be to recharge with good quality water that would maintain the existing use or even elevate it to a higher level. The recharge water quality would then not be worse than that of the natural groundwater in the particular aquifer. This principle should be adopted as a general rule and exceptions should need individual investigation and approval. An example of an exception would be the recharge of wastewater into highly saline aquifers (e.g. for disposal).

The natural quality of groundwater will also determine the extent to which blending with compatible water is possible without affecting the aquifer and the usability of the water.

Converting saline aquifers to useable water resources by means of artificial recharge is becoming increasingly popular. Suitable "brackish" aquifers in South Africa need to be identified where recharge with good quality water would gradually dilute or replace the ambient saline groundwater and make them usable.

4.4.2 Blending of source water and natural groundwater

Surface water used for recharge in an artificial recharge scheme is usually saturated with oxygen. Most groundwater, on the other hand, may still contain dissolved oxygen, but in general, deeper layers of the aquifer are more anoxic or even anaerobic. Thus, the relevant hydrochemical species such as iron, manganese and other metallic ions, as well as nitrogen and sulphur compounds, will be in the reduced form. The oxidation-reduction potential (Eh) of the recharge water will therefore differ significantly from that of the groundwater.

The oxygen content and Eh of groundwater vary from humid to arid regions. This is largely due to the presence of organic compounds that are more abundant in humid areas. The oxidation of such compounds consumes oxygen, causing reducing conditions at shallower depths in humid regions. Pyne (1995) describes Eh as one of the most important measurements for in situ groundwater, particularly when the iron and

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manganese concentrations are more than 0.1 mg/L. Likewise, dissolved oxygen (DO) is an important field measurement for both groundwater and surface water (Pyne, 1995). In the case of chlorinated surface water, the Eh may be elevated and the DO value may be more meaningful.

Groundwater abounds with micro-organisms that mostly originate from the soil horizon. Although chlorination may sterilize the recharge water, the microbiological activity in the aquifer is sufficient to promote bacterially-mediated reactions such as nitrification, denitrification, and reduction of sulphate, iron, and manganese when recharge water blends with groundwater. It may be impossible to modify the oxidation-reduction potential in the subsurface but compounds that will cause changes in the subsurface hydrochemistry can be eliminated. In this way, the recharge water can be made more compatible with the ambient groundwater.

4.4.3 Water-rock interactions

As indicated above, high quality surface water is generally well-aerated, that is, saturated with oxygen. Injection of such water into the aquifer introduces oxygen into areas which are less oxidising or even reducing. Similar to the interaction with the ambient groundwater, the significant change in oxidation-reduction potential has to be accepted, the only possibility being to limit the concentration of compounds that are sensitive to changes in Eh.

The geological material of primary aquifers is often deposited from lakes and other water bodies including marshes. This causes the material to be inherently reducing, as it will contain reduced ions and compounds such as ammonium, sulphide, and organic constituents. Oxidation of pyrite occurring in the aquifer matrix (also bacterially mediated) will increase the sulphate concentration of the groundwater and will also bring iron into solution. Should the recharge water also contain nitrate, it may be denitrified, but the reaction will enhance the oxidation of sulphide. These characteristics are also found in fractured aquifers of sedimentary origin (e.g. the quartzite in the Windhoek aquifer). Igneous rocks or intrusions, containing ammonium ions in the rock matrix, may also give rise to aquifers of reducing nature. In addition, unwanted constituents forming part of mineral assemblages in the geological matrix (e.g. arsenic present in pyrites) will also enter into solution. This is the case with the Calvinia breccia pipe which is highly alkaline and has strong reducing properties (Cavé & Tredoux, 2002).

In carbonate aquifers, the removal of calcium carbonate may be substantial. This may compromise the stability of the aquifer in the longer term (example: Vanderzalm *et al.*, 2002).

The sustainability of the intended artificial recharge scheme can be tested using the approach by Stuyfzand (2002) to predict and quantify the hydrogeochemical impact and sustainability of artificial recharge schemes.

4.4.4 Clogging

Clogging, or "plugging", (Pyne, 1995) refers to the reduction in permeability of the filtration surface of the recharge facility, or, the reduction in available pore volume and permeability in the aquifer. This phenomenon is complex and is due to a combination of physical, biological and chemical processes (Pérez-Paricio, 1998). The effect of filtration surface clogging can be observed readily in the reduction of the infiltration / injection rate. Aquifer clogging is more difficult to detect as it generally occurs gradually. In the case of injection boreholes, the surface area is relatively small and the phenomenon of clogging can be rapid and irreversible. It is generally more easily managed in basin recharge.

Various forms of clogging, each of which could be a combination of physical, biological and chemical processes, have been listed (Dillon & Pavelic, 1996; Pyne, 1995):

- Filtration of suspended solids
- Microbial growth
- Chemical precipitation
- Clay swelling and dispersion
- Air entrapment (or entrainment)
- Gas binding (release of dissolved or generated gases)
- Mechanical jamming and mobilisation of aquifer sediments.

Clogging is an operational problem largely related to the quality of the recharge water. However, site-specific conditions, such as aquifer and groundwater characteristics, borehole construction and recharge facility design, all influence the clogging process (Pyne, 1995). According to Rinck-Pfeiffer *et al* (2002), clogging remains the main factor affecting the feasibility of new ASR projects using low-quality source water. Biological clogging is considered to be of primary importance when nutrient-rich reclaimed water is injected into boreholes.

According to Dillon & Pavelic (1996), some 80 percent of ASR sites surveyed reported clogging problems. Half the sites reported physical clogging due to filtration of suspended solids. Microbial growth was a problem at 15 percent of sites and chemical precipitation caused clogging at 10 percent of sites. Other causes of clogging included air entrapment (10 percent), clay swelling and dispersion (5 percent) and mechanical jamming and mobilisation of aquifer sediments (5 percent).

Over the longer term, almost all artificial recharge schemes will be affected by clogging, although the rate and intensity of the problem will vary. For this reason, all schemes should make provision for remedial measures. However, Pérez-Paricio (1998) stated that prevention remained the best approach, in spite of the existence of sophisticated redevelopment techniques. Recharge water quality is the key factor and suspended solids are listed as the main criterion for both surface infiltration schemes and borehole injection. Other important parameters include pH, organic carbon concentrations and nutrients. In the case of artificial recharge by injection, air entrapment or gas generation should be avoided.

Adequate and timely identification of clogging generally leads to the opportunity to restore the initial capacity of the scheme by using a suitable redevelopment method (Pérez-Paricio, 1998). However, the prediction of clogging remains uncertain, despite many attempts at using parameters such as total suspended solids and turbidity for physical clogging, and total organic carbon, dissolved organic carbon and assimilable organic carbon for biological clogging.

The practical approach, as advocated by Pyne (1995), (Pérez-Paricio, 1998) and confirmed by Bouwer (2002), calls for site-specific pilot recharge tests for determining clogging potential of a duration of up to two years or more. Buik & Willemsen (2002) meanwhile developed an approach using a Fouling Index (called the MFI) for deriving physical clogging potential and demonstrated that the calculated values closely approximated the actual field data. They are of the opinion that all other forms of clogging (i.e. those caused by gas bubbles, bacteria and chemical reactions) can be prevented, and they state that physical clogging can be predicted and controlled.

In addition to clogging of the filtration surface and the aquifer, clogging of recovery wells may also occur (Moorman *et al.*, 2002). In the Amsterdam dune area, treated Rhine water with high oxygen content was injected into a deep aquifer with naturally anoxic water. The native groundwater had a relatively high iron content of 3 mg/L as well as other reduced chemical species. The recovery well clogged suddenly after two years' operation. The clogging material consisted mainly of ferric (hydr)oxides and ferric hydroxyphosphates, with hydroxyapatite as accessory deposit. Incompatibility of injected and aquifer water is discussed in paragraph C.1.4.2 above and water-rock interaction in paragraph C.1.4.3. Such interactions may be partially responsible for the mobilisation of the iron, although the native groundwater in the above example already had a high iron content. Although iron clogging occurred in the recovery borehole, such clogging is not limited to artificial recharge schemes but also occurs in wellfields where natural groundwater is abstracted.

4.4.5 Pre-treatment prior to artificial recharge

The extent of pre-treatment required will depend on:

- The type and quality of the source water
- The type of artificial recharge system employed
- The sustainability requirement of aquifer use
- The intended use of the recovered water.

The type of artificial recharge system and the clogging potential of the water will be important criteria in setting the treatment requirements for recharge water. The removal of suspended solids by flocculation and filtration would be widely applicable for reducing clogging potential. Further, water quality guidelines exist for all types of water use and these will determine the extent of required treatment. However, the interaction between the recharged water, the aquifer material and the ambient groundwater will determine the longer-term sustainability of using an aquifer for AR.

Following the above discussion on blending reactions and the hydrochemical water-rock interaction, pre-treatment principles need to be defined. The principles should include protection of the aquifer, taking potential interactions between the different components into account, and setting limits to any possible degeneration.

4.4.6 In situ treatment (including soil aquifer treatment)

The early artificial recharge schemes relied to a considerable extent on the soil/unsaturated zone and hydrochemical reactions in the saturated zone for in situ improvement of recharge water quality. Soil aquifer treatment (SAT) schemes generally rely on the ability of the soil to transform or remove from the recharge water contaminants that may affect groundwater quality (ASCE, 2001).

The Dan Region Project in the coastal region of Israel is the largest water reclamation scheme in the country and relies on SAT as an integral part of the wastewater treatment process (Idelovitch & Michail, 1984). However, the abstracted water from the Project was not intended for indirect recycling of treated wastewater, and the use of abstracted water for potable purposes was discontinued once the recycled water constituted more than 5 percent of abstracted groundwater. As a result of the limited pre-treatment with high lime dosage in the early stages of the project, breakthrough of contaminants occurred relatively soon. Subsequently, the reclaimed water was used for non-potable purposes, particularly unrestricted irrigation in the south of the country (Kanarek & Michail, 1996). In contrast, where potable recycling is intended, the natural processes during SAT are only relied on to "polish" treated wastewater (Fox, 2002).

Kopchynski *et al*. (1996) studied the effects of soil type and effluent pre-treatment on SAT, using different soils and effluents in soil column studies. The authors confirmed the need for wetting and drying cycles for optimum purification but found that low concentrations of residual organic carbon remained in the water despite variations in conventional pre-treatment. This leads to the conclusion that pre- or post-treatment may need to involve activated carbon adsorption or membrane filtration for removing organic compounds.

The extent to which an aquifer can serve to remove other constituents, such as heavy metals, will depend on policy decisions regarding the acceptable use of the soil-aquifer system and whether any degeneration should be allowed. Re-mobilisation of the pollutants is possible once the oxidation-reduction conditions in an aquifer change. Approaches by different countries are divergent but, in the Netherlands, pressures exist to reduce the "footprint" of artificial recharge activities, and even to restore hydrological systems to their more natural state (Olsthoorn & Mosch, 2002).

The application and effectiveness of in situ treatment relies largely on:

- The type of source water (and potential contaminants)
- The type of aquifer
- The final use of water
- The long term sustainability of the in situ treatment process
- The need for aquifer protection.

4.4.7 Post-treatment

The quality of the recovered water, and hence the need for post-treatment will depend largely on:

- The quality of the recharge water
- Interaction of the recharge water with the natural groundwater
- Rock-water interaction in the aquifer with the potential introduction of unwanted species into solution
- The subsurface retention period
- The intended use of the recovered water.

4.4.8 Water quality monitoring strategy

Water quality monitoring will need to fulfil a number of objectives:

- Provide detailed information on recharge water quality

- Demonstrate the efficiency of pre-treatment processes
- Provide details of background water quality in the aquifer
- Demonstrate that groundwater quality in the aquifer is maintained or improved
- Monitor the recovered water quality according to criteria for the intended use.

4.4.9 Public and environmental health risk

ASCE (2001) warns that failure to research the legal factors early in the process can lead to unnecessary delays and possible failure of the project. Careful attention to the identification of environmental impacts, as well as open communication with environmental groups, is necessary during the entire process. Two of the legal issues to be addressed are (ASCE, 2001):

- Controls on the use of reclaimed wastewater
- Liabilities associated with water quality issues.

Associated risks include, as an example, the use of reclaimed wastewater for any purposes that were not intended. Controls are necessary to prevent such an eventuality. Other risks may involve discharge into the environment of water unsuitable for recharge due to poor quality. Unforeseen discharges into the environment may also occur due to high water levels in the receiving aquifer. Other examples may include unforeseen quality variations of recovered water.

The risk assessment should cover the entire life cycle of the project, including decommissioning.

4.5 Artificial recharge method and engineering issues

The types of artificial recharge are described in Section B.1. This section describes the components of artificial recharge schemes and identifies some of the key issues relating to the recharge method and technical design. Successful schemes are well designed – both in terms of the effectiveness and efficiency of the infrastructure and the ease of operation and maintenance.

The key infrastructure components that form part of artificial recharge projects are shown in Figure 20.

The primary engineering function in artificial recharge scheme design is the sizing and matching of the various components:

- Source abstraction works
- Pump stations and pipelines
- Pre-injection treatment works
- Injection supply pumps and pipelines
- Injection boreholes and well head works
- Infiltration basins/trenches
- Abstraction boreholes, pumps and pipelines
- Post-injection treatment works
- Storage and distribution

The **source water** to supply the scheme is usually surface water, but can be groundwater (groundwater transfer scheme) or treated wastewater. Usually there is a seasonal fluctuation in the water availability and artificial recharge schemes are designed to store the excess water from the high flow periods. With this scenario, no new abstraction works are needed and the artificial recharge scheme can help to increase the use of the existing abstraction works, pump stations and pipelines.

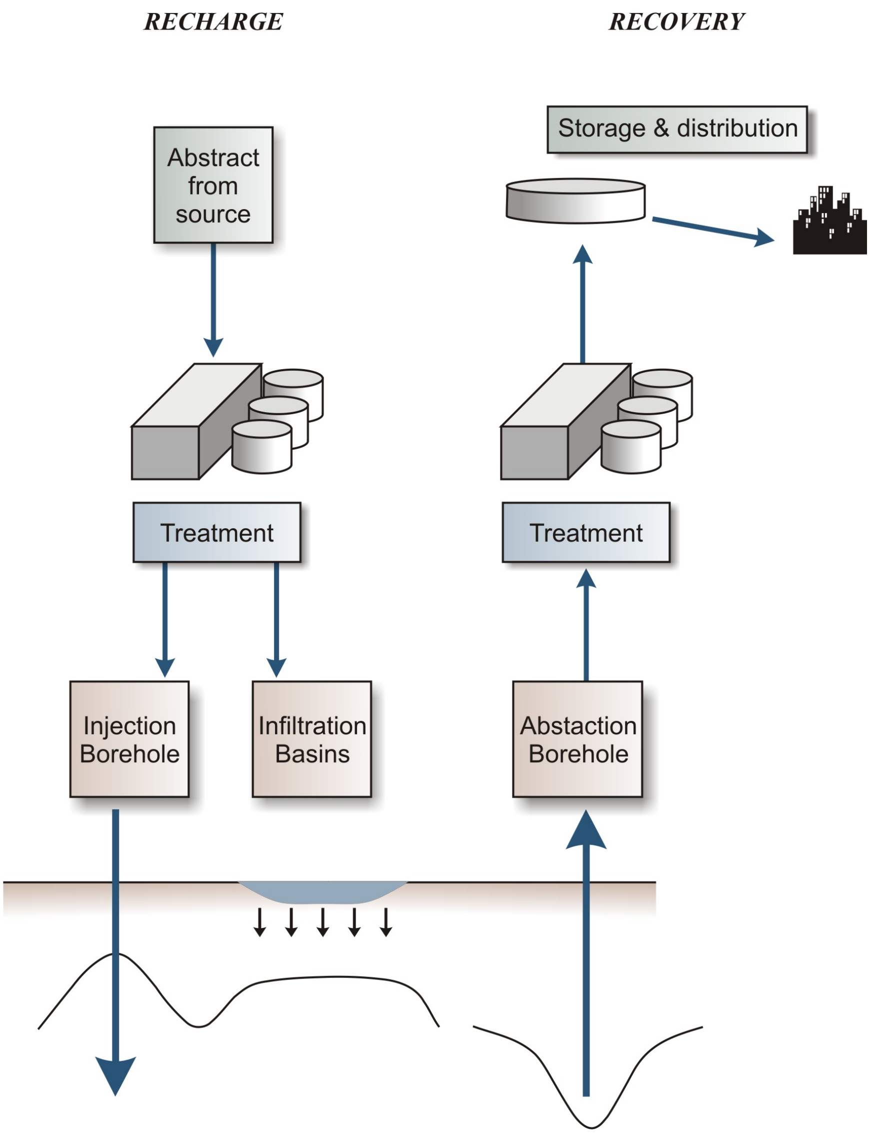

Figure 20: Infrastructure components of artificial recharge schemes

Lecture notes

The extent of **water treatment** required prior to recharge relates to the quality of the source water, the type of artificial recharge system employed and the intended use of the recovered water. Minimising clogging is a key design factor, and this relates directly to the quality of the recharge water and the type of artificial recharge scheme (see Section C.1.4). Post-recharge treatment requirements depend on the intended use of the recovered water.

Key engineering issues are:

- Which artificial recharge method is most efficient and cost-effective?
- Are the engineering logistics practical and cost-effective regarding the transfer of source water to the point of recharge; and from the point of abstraction to the point of consumption?
- How can the scheme be designed to minimise clogging?
- The design must be appropriate for the operation and maintenance skills levels.

Artificial recharge method. The most efficient artificial recharge method to be used must be assessed based upon the site-specific conditions that include:

- The quality of the water used for recharge.
- The hydrogeological environment.
- Existing infrastructure and the costs of additional infrastructure required.
- The management and technical capacity needed to operate the scheme.

Cooperative planning between the engineering, hydrogeological and geochemical disciplines during the conceptual design stage is the best approach to ensure that the artificial recharge scheme is well planned and makes maximum use of available resources.

In order to design a cost effective scheme that makes best use of existing infrastructure, it is necessary to establish the capacity and operating procedures of existing water supply infrastructure. Understanding the capacity and level of use of the different components of the supply system will assist in designing an artificial recharge scheme that optimally uses existing infrastructure and minimises new infrastructural required. This is particularly true of pipelines, above ground storage and treatment facilities.

In Plettenberg Bay, where the feasibility of artificial recharge is being assessed, an additional benefit to water supply during their high summer peak demand period, is that with artificial recharge, they would use their existing water treatment plant to capacity during the low-demand period, and thereby extend its design life. Treated water would be stored in the off-peak winter months, to be used in the summer months without having to pass through the treatment plant again. The treatment plant can operate at higher capacity during low-demand times, and not be stretched to capacity throughout the high-demand times.

Incremental development. Artificial recharge schemes are usually developed incrementally, where increases in capacity are based on the performance of the system during initial operation. Thus infrastructure planning needs to accommodate the initial artificial recharge development, but must identify the requirements for future increases in scheme capacity. Where new infrastructure such as pipelines and treatment facilities are required, it is usually cost effective to design these for the full capacity of the scheme.

Borehole and wellhead design. Existing boreholes are often suitable for injection, however, if new boreholes are planned, the following requirements must be taken into account:

- Material for piping both above and below ground should be non ferrous to minimise the potential of to minimise the potential of corrosion and rusting.
- Provide facilities for pipeline flushing and waste flow discharge.
- Provide sampling taps for water quality sampling of both recharge and recovered water.
- Design down-hole flow control (either fixed or variable) to ensure that cascading does not occur.
- Remove or minimise air from the recharge water prior to injection.
- Ensure that the pipelines remain under a positive pressure or design for negative pressure pipelines to avoid pipeline collapse.

4.6 Environmental issues

Artificially recharging groundwater can have both detrimental and positive impact on the environment. These are listed and briefly described in Section B.1. A common motivation for artificial recharge schemes is the rehabilitation of impacted environments. In South Africa this would typically be recharging of aquifers that were previously overexploited or mined. In other parts of the world artificial recharge schemes have been used to rehabilitate groundwater dependent ecosystems like in the case of the Florida everglades (Pyne, 2005).

The main environmental concerns associated with artificial recharge schemes relate to the lowering and raising of water tables (or piezometric levels) over and above those of existing use, and issues associated with water quality changes within the aquifers. Table 14 lists key potential negative impacts.

Table 14: Potential negative environmental impacts of artificial recharge schemes

Effects	Consequence
Raised groundwater levels	**Vegetation dieback** Raising the water table close to the soil surface may cause vegetation dieback as a result of soil saturation or the establishment of invasive alien plants. **Damage to structures** Destabilize or damage structures such as roads or buildings. **Pollution** A raised water table is more vulnerable to contamination by industry, wastewater disposal facilities, cemeteries etc. **Flooding** Raising the water table may exacerbate flooding during wet periods due to surface saturation and reduction in the ability of water to infiltrate. **Discharge of foreign water into wetlands and rivers** Changes in the wetland environment such as water temperature, oxygen levels, pH, turbidity, salinity, maximum and minimum water depths, could have an effect on groundwater-dependant species (fish, invertebrates, amphibians) and ecosystems (Brownlie, 2005). The pH, turbidity and salinity of the groundwater is often fairly constant due to long retention times and the organisms that depend on this water can be sensitive to fluctuations in water quality.

Effects	Consequence
	Salinisation by increased evaporation The salinity of water in near-surface water tables can increase due to evaporation.
Lowered groundwater levels	**Wetlands and rivers** Depending on the relationship between surface and groundwater, the lowering of groundwater levels could affect river flow regimes (including baseflow), and wetland and riverine ecosystems. Seeps may be important breeding or feeding areas for birds and other wildlife. Changes in water level or water quality may affect habitat quality and wetland function (e.g. flood control). **Trees** Roots of some large trees reach aquifers. Rooting depths of tropical savanna trees averages 15 m, for desert trees 10 m, and riparian trees such as Acacia karroo have roots at 10-25 m below ground level (Canadell *et al*. 1996). Dewatering, or large fluctuations in the water table may change vegetation structure and composition by causing dieback of riparian trees (Le Maitre *et al* 1999). This in turn will change habitats for birds and other animals that depend on woodland patches, particularly in arid environments. Drainage line woodlands are movement corridors for many animal species. Woodland dieback may reduce the stability of alluvium during floods. Woodland dieback has aesthetic as well as biodiversity consequences. **Land subsidence** Land subsidence can occur in particular environments (especially in unconsolidated sediments) if groundwater levels are significantly lowered. Dolomitic aquifers are vulnerable to sinkhole formation. **Drying up of boreholes** Other groundwater users could be affected.
Water quality issues	**Clogging** This refers to the clogging in and around recharge boreholes due to chemical precipitation or microbiological growth. This has consequences for recharge capacity and borehole rehabilitation or replacement costs. **Mobilising undesirable chemical constituents** Determinands such as existing arsenic in an aquifer can be mobilized by lowering the water table and creating an oxidising environment. The health of groundwater users (domestic, industry, livestock and irrigation) could be affected by the release of such constituents. **Aquifer organisms** The transfer of foreign water into an aquifer with different characteristics and quality could be problematic for the aquifer organisms. This applies particularly to water of impaired quality and treated waste water. There may be residual concentrations of chemicals such as chlorine in the water, which could have a detrimental impact on organisms in the aquifer.

The extent and significance of the abovementioned impacts would depend on numerous site-specific factors. In environmentally-sensitive areas it may be necessary to place operational restrictions on schemes, like only allowing water level fluctuations between a few metres below the top of the aquifer and the lowest natural water levels.

In the environmental study that forms part of an artificial recharge feasibility assessment, potential environmental issues need to be identified and where appropriate, baseline ecosystem data collected and ecological monitoring requirements identified. The risk and reversibility of environmental impacts should be discussed. Risks relates to the significance of the potential impacts, and the likelihood of those impacts occurring. Depending on the extent of available data, it may not be possible to adequately define risks, and a comprehensive monitoring plan may be needed.

Aquifers which are well monitored and well understood carry less risk, and it is easier to predict the consequences of artificial recharge and make informed management decisions. Environmental risks depend on a number of factors inter alia the nature of the source of the water, the volume of recharged water, aquifer parameters, the sensitivity of groundwater-driven ecosystems and the extent and nature of existing aquifer use.

The concept of reversibility is critical when considering the significance of an impact. Determining how quickly a component of the environment could recover from a particular stress due to groundwater recharge is challenging. If impacts are irreversible or only reversible over long periods of time, the significance of the impacts are that much greater, and may be considered to be unacceptable. Impacts on the built environment are more easily and quickly reversible through engineering solutions than impacts on the biophysical environment. However, impacts on the biophysical environment can be more challenging to reverse, and commonly happen over a longer period of time.

A risk management approach to implementing artificial recharge schemes based on the informed precautionary principle should be adopted after identifying all potential problems (Dillon, 2005).

The extent, magnitude and significance of environmental risks associated with artificial recharge schemes need to be discussed (in the feasibility study) in relation to the benefits of the scheme (both water supply and environmental), and compared with alternative water supply options.

4.7 Legal and regulatory issues

All artificial recharge schemes need to need licensed. Obtaining the necessary permits is thus crucial to the success of new projects. The key legal issues regarding the assessment and operation of artificial recharge schemes include:

- Water use licensing for artificial recharge schemes
- Environmental authorisation requirements for both testing and implementing the scheme (i.e. Basic Assessment or Environmental Impact Assessment)
- Environmental Management Plans (EMPs)
- Compliance with regulations (e.g. relating to water reuse)
- Rights associated with the use of artificially recharged water.
- Compliance with the conditions and reporting requirements of the water use licence and environmental authorisation.

Artificial recharge schemes need to be licensed because storing water underground is defined as a "water use" in the National Water Act.

Artificial recharge cannot be excluded from licensing under pretext of a general authorisation, as the storage of water underground is specifically excluded from general authorisation.
(Government Notice No 26187 of 26 March 2004)

4.8 Economics

Unused aquifer storage capacity can often be developed at a significantly lower cost than surface storage facilities, and without the adverse environmental consequences frequently associated with surface storage (Pyne, 1995). In relation to water treatment, natural attenuation of waste water using aquifer media is a cost-effective means of improving water quality.

When undertaking economic option analyses, it is important to evaluate all options on the same basis, and to include all capital and operational costs. The Windhoek case study in Section B.3 provides a good example of a comparative cost assessment.

In the Windhoek economic assessment, the proposed artificial recharge scheme was compared to alternative water supply options for Windhoek and other recent or planned projects in the central region of Namibia (SWECO, 2002). Windhoek's priority was to increase the security of supply and on that basis the following four factors were evaluated:

1. Present worth cost including the following costs and revenues:

   - Initial capital investment cost
   - Annual depreciation and residual value (discounted to present value)
   - Average incremental annual pumping cost
   - Average incremental annual operation and maintenance cost

2. The incremental security of supply (ISS). The study modelled the supply for each scenario as well as a baseline "do nothing" scenario. The ISS is the difference between the expected annual shortfall of the particular scheme scenario and the "do nothing" scenario during a 10 year planning period. The ISS is measured as a volume per year.

3. Water Saving (or scheme efficiency) based on evaporation losses for each alternative scheme

4. Ratio of cost to ISS (in R/annual volume).

Other factors that could be assigned an economic value include:

- The strategic value of drought mitigation measures
- The efficient use of local resources compared with developing sources in other distant areas

An economic study should compare the cost per cubic meter of water supplied for each alternative supply option. It is important that the same method be used to price water. This is particularly important when water is purchased from a bulk water provider such as a water board or when compared with existing schemes, as the price of water may be subsidised.

Figure 21 describes the different levels of water pricing adopted in the Windhoek economic assessment (SWECO, 2002). In many cases water is priced only on the financial cost, but ideally, an accurate comparison should be based on the total water supply cost.

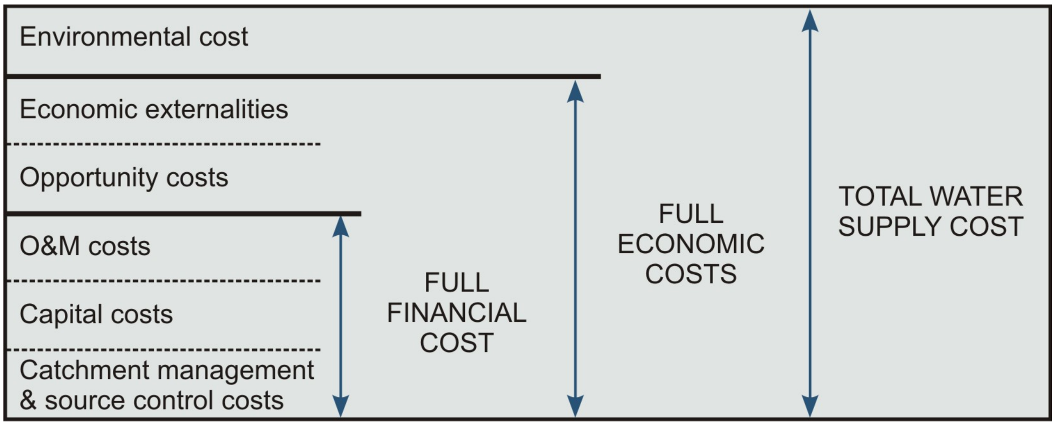

Figure 21: Levels of water pricing (after Heyns, 1998)

For small to medium municipal scale projects, DWAF's Typical Unit Cost for Water Services Development Projects: A Guide for Local Authorities (DWAF, 2003) provides a uniform tool for estimating the cost of water supply options.

4.9 Management and technical capacity

The successful operation of an artificial recharge facility depends largely on an effective management strategy and on the availability of sufficiently skilled or competent staff to carry out the necessary tasks. Maximum benefit from an artificial recharge scheme involves integrating the scheme into the planning and management of the overall water supply system. Depending on the scale of the artificial recharge scheme, this can include management of the entire catchment. The overall aim is to optimise both surface and groundwater resources and their storage capacities.

Artificial recharge schemes commonly involve surface or waste water capture, treatment, pumping, water quality monitoring and clogging control. Careful planning and management is required to ensure that these processes are efficient. This assumes the availability of competent personnel who, in the case of large facilities, need to be dedicated solely to the task of managing the scheme. In such cases, the responsibility of operating the scheme should not be viewed as just another task of the water supply engineer, but rather as another water resource that requires a manager.

In some cases, management requirements are minor, such as the Kharkams scheme in Namaqualand where weekly inspections during operations are sufficient. In other cases, and in particular where water quality management is critical for clogging or health reasons, relatively high-level technical management is required. In both cases, however, artificial recharge management is critical for the successful operation of the scheme.

Knowledge of the following subjects may be needed to operate an artificial recharge scheme successfully:

Lecture notes

- Hydrogeology of the basin
- Integrated water cycle of the catchment and source water supply
- Recharge and recovery technology
- Groundwater level monitoring
- Water treatment and water quality management
- Water supply engineering.

There is currently a shortage of technical skills in South Africa, especially at the municipal sphere of government. Artificial recharge project feasibility studies must identify the technical and management skills required to operate the scheme and from where the skills will be sourced and funded.

The technical skills required to assess the feasibility and to design an artificial recharge scheme vary with the type and size of the scheme and may include:

- Geology
- Hydrogeology
- Aquifer simulation modeling
- Hydrology
- Geochemistry
- Environmental impact assessment
- Pipeline hydraulics
- Borehole and pump station design
- Water treatment

Other skills may be required to address legal and regulatory issues. Failure to accommodate all of these disciplines at the planning and conceptual design stages can lead to costly mid-course corrections, or even scheme failure.

4.10 Institutional arrangements

Associated with artificial recharge scheme licences are monitoring and reporting requirements. The institutional capacities of both the scheme operator and the regulatory authority need to be sufficient to ensure that the scheme is operated according to design standards. This applies particularly when water of marginal quality is used for recharge. If the scheme operators or regulatory authorities lack the capacity to manage and "oversee" schemes, the schemes will lose efficiency through clogging, poor maintenance, etc, and perform well below design capacities. Reporting and performance monitoring systems need to be in place to maintain optimal scheme operation.

Besides small-scale individual (typically farmer) artificial recharge operations, the responsible authorities for authorising, licensing and operating artificial recharge schemes could include:

- DWAF/CMA
- Water Services Authority (WSA)
- Water Services Provider (WSP), including Water Boards (WB)
- Water User Association (WUA)
- DEAT

While the institutional arrangements are clear with respect to water services provision (DWAF, 2004e), such arrangements have as yet, not been considered for artificial recharge applications. The key issues relate to:

- Licensing
- Monitoring
- Water quality control
- Financial arrangements
- Rights to the use of recharged water
- Reporting
- Support.

The institutional framework for artificial recharge management is presented in Table 15.

	DEAT regional office		Licensee or user		Catchment Management Agency
Key legal responsibilities	Overall environmental resource management	Environmental authorisation conditions (→) Information & reports (←)	Operate schemes according to licence conditions	Licence Conditions (←) Information & reports (→)	Overall water management within the CMA
Responsibilities with respect to monitoring and management of AR schemes	Support users to establish environmental monitoring requirements Ensure users know their monitoring & reporting responsibilities Review reports and environmental permits	Information & reports (←) Support & monitoring (→)	Manage, operate and monitor schemes within the conditions of the water use licence and environmental permit Collect monitoring data on water quality, water levels, abstraction injection and environmental aspects Store & process monitoring data and compile reports for the CMA/DWAF and DEAT. Analyse data and recommend operational changes	Information & reports (→) Support & monitoring (←)	Support users to establish the groundwater & AR management needs Ensure users know their monitoring & management responsibilities Draft water use licences to include monitoring, data and reporting requirements Review reports and licences

Table 15: Institutional framework for artificial recharge management

Lecture notes

Many artificial recharge schemes rely on cooperation between water services authorities, bulk suppliers and water resource management institutions. In Windhoek, for example, large-scale borehole injection has been put on hold until agreements between the source water supplier (NamWater) and the manager/user of the scheme (the City of Windhoek) have been finalised.

The seriousness of "getting the institutional arrangements sorted out" cannot be overemphasised. Eight out of ten of the most significant impediments to implementing a cost-effective conjunctive management program in California related to institutional issues (Utah, 2002). The identified impediments are listed below, and should be anticipated in project planning:

- Inability of local and regional water management governance entities to build trust, resolve difference (internally and externally), and share control.
- Inability to match benefits and funding burdens in ways that are acceptable to all parties, including third parties.
- Lack of sufficient federal, state and regional financial incentives to encourage groundwater conjunctive use to meet state-wide water needs.
- Legal constraints that impede conjunctive use, regarding storage rights, basin judgments, area of origin, water rights, and indemnification.
- Lack of state-wide leadership in the planning and development of conjunctive use programs as part of comprehensive water resources plans, which recognize local, regional, and other stakeholders' interests.
- Inability to address quality differences in "put" versus "take"; standards for injection, export, and reclaimed water; and unforeseeable future ground water degradation.
- Risk that water stored cannot be extracted when needed because of infrastructure, water quality or water level, politics, and institutional or contractual provisions.
- Lack of assurances to prevent third-party impacts.
- Lack of creativity in developing lasting "win-win" conjunctive use projects, agreements, and programs.
- Supplemental suppliers and basin managers have different roles and expectations in relation to conjunctive use.

5. GUIDELINE DOCUMENTS

5.1 General artificial recharge guideline documents

5.1.1 Draft Code of Practice for Aquifer Storage and Recovery

Reference:	Dillon (2005). Draft Code of Practice for Aquifer Storage and Recovery. CSIRO Land and Water, Australia.
Availability:	This is an updated version of the document of the same title by the South Australia Environmental Protection Agency (2002).
Number of pages:	24 (paper size: A4).

Major issues:
The following issues are listed as "Guiding Principles for Best Practice":

1) *Risk management.* This should account for uncertainty in aquifer characteristics, variations in water source quality and quantity, and changes in land uses and management that may take place over the operating life of the ASR scheme.
2) *Prevention of irreparable damage.* Although it is recognised that all the information required to predict the performance of an ASR/ASTR site will not be available until the site is operational, it is nevertheless necessary to identify all foreseeable modes of failure, take preventative action to ensure that these do not occur, and identify contingency plans to prevent irreparable damage.
3) *Demonstrations and continuous learning.* Emphasis is placed on monitoring in order to understand the systems better.
4) *Informed precautionary principle.* A risk management approach should be adopted after identifying all potential problems.
5) *Water quality requirements.* The quality of the water injected should be determined by the designated environmental values (beneficial uses) of native groundwater in the aquifer.
6) *Attenuation zone.* Cognisance of attenuating properties of aquifer media (to reduce contaminant properties) should be taken into account.
7) *Rights of water bankers and recoverable volumes.* The guiding principle should be that water stored in the aquifer is available to the operator of the ASR scheme.
8) *Finite storage capacity of aquifers and interference effects between sites.* In licensing ASR schemes, the aquifer's storage capacity and the spacing of adjacent ASR schemes must be taken into account.

Comment on the document:
This Code of Practice outlines the requirements of the Environmental Protection Agency and the Department for Sustainable Development within the State of Victoria, Australia. It provides guidance for projects intended to store water for drinking, irrigation, industrial and ecosystem support purposes, but not for waste water disposal purposes. Source waters include drinking water, stormwater, reclaimed water and groundwater.

Much of the focus on ASR in Australia has been on water quality issues, and hence the Code of Practice covers these issues in greater detail than other issues such as the ability of aquifers to receive injected water (hydraulic issues).

The document refers to the challenge of coordinating environmental regulation and water resource management roles in the approval of new projects.

The Code of Practice includes, amongst other topics:

- Groundwater protection policies in relation to ASR (including injectant water quality criteria)
- Procedure for licence application
- The components of ASR systems
- A generic plan to assess and manage the risk of polluting groundwater and failure to meet required water quality criteria for the recovered water (the Hazard Analysis and Critical Control Point Plan – HACCP) .

5.1.2 Standard Guidelines for artificial recharge of Groundwater

Reference:	American Society of Civil Engineers. 2001. Standard Guidelines for artificial recharge of Ground Water, EWRI/ASCE 34-01. ISBN: 0784405484.
Availability:	ASCE website: www.asce.org (bookstore: www.pubs.asce.org).
Number of pages:	106 (paper size: A4).

Major issues:
This document provides a comprehensive overview of the issues that affect the planning, design, construction, operation and closure of various types of artificial recharge scheme. In so doing, it identifies many issues that have to be dealt with for the successful implementation of an artificial recharge scheme. These include technical, environmental, legal, economic and social issues.

Comment on the document:
This document summarises the issues that need to be considered when taking an artificial recharge project from its conception stage, through construction and operation, to closure. The chapter headings are:

1) General (including purpose and types of schemes)
2) Planning
3) Field investigations and field testing
4) Design
5) Regulatory and water rights issues
6) Environmental issues
7) Economics
8) Construction
9) Start-up, operation and shutdown procedures
10) Operation, maintenance and closure

The document does not claim to provide a comprehensive "how to" guideline on each topic, but rather aims to describe the many steps required to develop, operate and maintain an artificial recharge project. In this regard, it is comprehensive, and although it generally offers little information on how to address the issues, it goes into greater depth on certain topics, such as those regarding the use of treated waste water.

This document can be used as a good checklist of issues that need to be taken into account when planning an artificial recharge scheme.

5.1.3 Groundwater Recharge and Wells: A Guide to Aquifer Storage and Recovery

Reference:	Pyne, R.D.G. 2005. Aquifer Storage Recovery: A Guide to Groundwater Recharge through Wells. Second Edition. ASR Press, Florida, USA.
Availability:	ASR Systems, PO Box 969, Gainsville, Florida, 32602, USA.
Number of pages:	608 (paper size: between A4 and A5).

Major issues:
The book raises and addresses most of the issues pertaining to ASR schemes. A major focus is on implementation stages, scheme design, water quality and geochemistry (and associated issues such as clogging), and the book includes information on a number on other technical and non-technical issues.

The book is divided into the following chapters:
Introduction
1) ASR Programme development
2) Design of ASR systems
3) Selected ASR technical issues
4) Geochemistry
5) Selected ASR non-technical issues
6) Alternative ASR applications
7) Selected case studies
8) Future directions

Comment on the document:
The book provides a comprehensive description of all the key issues affecting ASR schemes. It has been updated to include, amongst other topics, the considerable research that has gone into assessing the fate of pathogens during subsurface storage.

The book describes how to undertake feasibility studies and has an in-depth section on design issues. It includes an in-depth section of water quality issues, including pre- and post-treatment, geochemical issues and clogging.

This is the definitive guide to ASR, accompanied by numerous case studies.

5.1.4 Artificial Recharge of Groundwater: Hydrogeology and Engineering

Reference:	Bouwer, H. 2002. Artificial recharge of groundwater: hydrogeology and engineering. Hydrogeology Journal (2002) 10:121-142. Springer, Heidelberg, Germany.
Availability:	Hydrogeology Journal.
Number of pages:	21 (paper size: A4).

Major issues:
In this paper, Herman Bouwer summarises the key issues that affect the design and operation of artificial recharge schemes. Emphasis is placed on infiltration basins, on which subject Prof Bouwer has vast experience.

The key topics covered include:

- The mathematics of, and the factors that affect, infiltration from surface recharge schemes (including soil clogging)
- The role of recharge in water reuse.

The governing equations of infiltrating water are summarised in this paper, but are dealt with in greater detail in numerous other groundwater and engineering text books. These include those written, or contributed towards, by Prof. Bouwer in Huisman and Olsthoorn (1983) and in other journal papers.

Planned water reuse is expected to become increasingly important in future, and artificial recharge is identified as a cost-effective means to utilise surplus waste water. This option is "often cheaper than the treatment for discharge into surface water that is necessary to protect in-stream and downstream users of that water against unacceptable pollution".

The paper presents a practical approach to implementing artificial recharge schemes: "Design and management of artificial recharge systems involves geological, geochemical, hydrological, biological and engineering aspects."

> *"Because soils and underground formations are inherently heterogeneous, planning, design and construction of groundwater recharge schemes must be piecemeal, first testing for fatal flaws and general feasibility and then proceeding with pilot and small-scale systems until the complete system can be designed and constructed." Bouwer, 2002.*

Comment on the document:
Prof. Bouwer is one of the world's leading experts on surface recharge schemes. This paper consists of a summary of the key issues affecting flow from surface recharge facilities. For an aquifer to receive recharged water, it needs to be sufficiently transmissive, and this must be established by field investigations.

This document provides a succinct summary of concerns regarding the use of waste water in artificial recharge facilities, and summarises the advantages (water quality improvements) associated with soil aquifer treatment.

5.1.5 Artificial Recharge: A Technology for Sustainable Water Resource Development

Reference:	Murray, E.C. and Tredoux, G. 1998. Artificial recharge: A technology for sustainable water resource development. Water Research Commission, Report No 842/1/98. Pretoria, South Africa.
Availability:	Water Research Commission.
Number of pages:	152 (paper size: A4).

Major issues:
The key issues identified and discussed are:

1) Hydrological factors:
    - Recharge water sources: quantity, quality and reliability
    - Soil matrix chemistry and water quality issues
    - Hydraulic factors
    - Clogging potential
    - Numerical modelling
    - Recovery efficiency

2) Socio-Economic issues:
    - Economic
    - Management
    - Legal
    - Social

Comment on the document:
The document includes a section on "Guidelines for establishing artificial recharge schemes". The document is divided into the processes that are required for planning recharge basins and ASR schemes.

5.1.6 Artificial Groundwater Recharge

Reference:	Huisman, L. and Olsthoorn, T.N. 1983. Artificial Groundwater Recharge. Pitman Advanced Publishing Programme, Boston, London, Melbourne.
Availability:	Pitman Advanced Publishing Programme, Boston, London, Melbourne.
Number of pages:	310.

Major issues:
This text book covers the key technical issues relating to artificial recharge.

5.1.7 Guide on Artificial Recharge to Ground Water

Reference:	Central Groundwater Board. 2000. Guide on Artificial Recharge to Ground. Ministry of Water Resources, New Delhi, India.
Availability:	Central Groundwater Board, Ministry of Water Resources, New Delhi, India.
Number of pages:	93.

This document covers the planning of artificial recharge projects; artificial recharge techniques and design; project monitoring; and case studies. The appendices include a format for preparation of artificial recharge projects; a checklist for planning artificial recharge projects; and guidelines for evaluating artificial recharge projects.

5.2 Issue-based artificial recharge guideline documents

5.2.1 Clogging and artificial recharge of groundwater

Reference:	Pérez-Paricio, A. and Carrera, J. 1999. Clogging Handbook. EU Project on artificial recharge of groundwater. Contract ENV4-CT95-0071. Technical University of Catalonia (UPC), Barcelona, Spain.
Availability:	Uncertain.
Number of pages:	184 (paper size: A4).

Major issues:
All forms of clogging.

Comment on the document:
This is the most comprehensive document on all aspects of clogging in both surface and borehole recharge schemes. It includes clogging processes, prevention, redevelopment practices, how to detect and measure clogging, and empirical and numerical models for predicting clogging.

5.2.2 Guidelines on the Quality of Stormwater for Injection into Aquifers for Storage and Re-use

Reference:	Dillon, P.J. and Pavelic, P. 1996. Guidelines on the quality of stormwater and treated wastewater for injection into aquifers for storage and reuse. Urban Water Research Association of Australia. Research Report No. 109. ISBN 1 876088 13 3.
Availability:	Centre for Groundwater Studies, Flinders University, GPO Box 2100, SA 5001, Australia.
Number of pages:	48 (paper size: A4)

Major issues
The guidelines cover:

- Licensing
- Pre-treatment
- Monitoring
- Guidance for maximum contaminant concentrations in injectant
- Residence time prior to recovery
- Management of ASR operations.

Comment on the document:
The document reviews international practice and guidelines for artificial recharge of reclaimed waters by injection. It differs from other guidelines in that it does not assume potability as an essential objective, and it caters for treatment of the water by natural processes in the aquifer.

5.2.3 Guidelines for the Use of Reclaimed Water for Aquifer Recharge

Reference:	DNDE 1982. Guidelines for the use of reclaimed water for aquifer recharge. Department of National Development and Energy. Australian Water Resources Council: Water Management Series No. 2, Australian Government Publishing Service, Canberra. ISBN 0 644 01892 5.
Availability:	Uncertain.
Number of pages:	103 (paper size: A4).

Major issues:

1. Reclaimed water characteristics:
   - Degree of treatment
   - Toxic contaminants
   - Salinity
   - Biochemical oxygen demand
   - Suspended solids

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- Temperature.

2. Aquifer characteristics:
   - Aquifer types – confined/unconfined
   - Aquifer zones – saturated/unsaturated zones.
3. Infiltration effects:
   - Chemical effects of infiltration through the unsaturated zone
   - Effects of infiltration on biological characteristics
   - Product water quality
   - Disinfection
   - Long-term effects on recharge.

Comment on the document:
Rather than providing clear guidelines, the document describes the issues that affect artificial recharge using reclaimed water. It provides information on operation and management, including:

- Hydraulic loading and treatment
- Nitrogen removal
- Phosphorus removal
- Pathogen removal
- Sampling and examination of water
- Monitoring the water table.

5.2.4 Artificial Groundwater Recharge – State of the Art

Reference:	Frycklund, C. 1992. Artificial Groundwater Recharge – state of the art. VA-FORSKs Raport Series, Sweden. ISBN No. 91-88392-08-2.
Availability:	Uncertain.
Number of pages:	55 (Paper size: A4)

Major issues:
This document focuses on the precipitation of iron and manganese, including bacterial activity that promotes iron and manganese oxidation and precipitation.

Comment on the document:
The document provides a thorough description of the chemical evolution of iron and manganese during recharge processes.

5.2.5 The Potential for Aquifer Storage and Recovery in England and Wales

Reference:	Jones, H. K. Macdonald, D. M. J. and Gale, I. N. 1998. The potential for aquifer storage and recovery in England and Wales. British Geological Survey. Technical report No. WD/98/26.
Availability:	British Geological Survey.
Number of pages:	36, excluding appendices (paper size: A4).

Major issues:
1) The development of an approach to establish an aquifer's ASR potential
2) Guidance on dealing with authorisations for artificial recharge and recovery schemes (Appendix J).

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Comment on the document:
This report identifies and describes briefly the main factors that affect ASR schemes. It draws heavily from Pyne (1995).

The issues covered are:

- Recovery efficiency
- Clogging
- Aquifer properties
- Operational issues
- Regulatory issues
- Hydrogeological factors (aquifer properties; depth to formation; aquifer confinement; aquifer water quality).

The value of this document, outside of the United Kingdom, is twofold: Firstly, it attempts to develop an approach to assess ASR sites on a regional scale. Although the first approach is abandoned, it nevertheless describes the proposed criteria and weighting system, and this can be used as a starting point to further develop a regional approach to assessing ASR potential. The factors that were considered were aquifer properties, aquifer confinement, depth to the aquifer and aquifer water quality. The finally adopted approach was largely based on geology and transmissivity.

The second major value of this document is that it provides guidance on dealing with authorisations for artificial recharge and recovery schemes (Appendix J). The guide is "reasonably" generic, although it refers, in places, to UK-specific criteria or regulations. Supporting material includes:

- Issues that would need to be covered in an environmental impact appraisal (Appendix J1)
- A summary of (UK) authorisations required for developing artificial recharge schemes (Appendix J2)
- A decision matrix for abstraction consenting and licensing (Appendix J3).

This document provides a sound basis from which to develop a generic authorisation guide.

5.2.6 Groundwater Licensing Guide – application procedure for the development and use of groundwater

Reference:	Parsons R, Eichstadt L, Crowther J and Blood J, 2006. Groundwater Licensing Guide – application procedure for the development and use of groundwater. WRC Project K5/1510. Water Research Commission. Pretoria, South Africa.
Availability:	Water Research Commission (In press).
Number of pages:	28 (paper size: A4).

Major issues:
The groundwater licensing guide considers legislation applicable to groundwater use in South Africa, and identifies when a licence and environmental authorisation is required.

Comment on the document:
As updated environmental regulations have only recently been promulgated, definitions, procedures and processes have not been tested, and thus the recommended

groundwater licensing guide itself still needs to be tested. The guide provides some useful tools and documentation related to licence applications.

5.3 Environmental guideline documents relevant to artificial recharge

5.3.1 Guidelines for involving hydrogeologists in EIA processes

Reference:	Saayman, I (2005) Guidelines for involving hydrogeologists in EIA processes - Edition 1; CSIR Report No ENV-S-C 2005 053 D. Republic of South Africa, Provincial Government of the Western Cape, Department of Environmental Affairs & Development Planning, Cape Town.
Availability:	This document can be downloaded from the DEADP website: http://www.capegateway.gov.za/eng/yourgovernment/gsc/406/publications
Number of pages:	54 (paper size: A4).

Major issues:
This document is one of a series of guideline documents pertaining to the EIA process in South Africa. It aims to give guidance as to when a qualified geohydrologists should be involved. It identifies three triggers that require the EIA practitioner consult a hydrogeologists:

- Where influent or chemicals with the potential to change groundwater quality is handled as part of the project or discharged into the environment due to the project.
- The volume of groundwater in storage or entering groundwater storage is changed beyond what is allowed by the DWAF general authorisations.
- The groundwater flow regime is changed.

Once the need for a hydrogeologists to be involved in the project is assessed, the document provide some guidance for drawing up terms of reference, specific tasks that the hydrogeologists may be involved in and specialised input and management actions.

Comment on the document:
The guideline document is unlikely to be particularly useful in any projects involving artificial recharge as a hydrogeologist would always be involved. However, the document provides useful guidance on how to review specialist report, how to address issues such as cumulative impacts and communicating the findings of specialist inputs.

5.3.2 Guideline on the interpretation of the listed activities requiring environmental authorisation

Reference:	DEADP (2006) Guideline on the interpretation of the list of activities; NEMA environmental impact assessment regulations guideline and information document series, Department of Environmental Affairs and Development Planning, Cape Town.
Availability:	This document can be downloaded from the DEADP website: http://www.capegateway.gov.za/eng/yourgovernment/gsc/406/publications
Number of pages:	70 (paper size: A4).

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Major issues:
In response to promulgation of new regulations pertaining to environmental impact assessment, DEADP produced a guide document on the interpretation of listed activities. Artificial recharge is not addressed directly in the guide, but associated listed activities that may be applicable to artificial recharge projects are.

Comment on the document:
The guide is useful in that it provides an interpretation of listed activities that may be relevant to artificial recharge. It also lists activities that may be pertinent to groundwater abstraction, such as the construction of pipelines, the transformation or removal of indigenous vegetation of 3 ha or more, and the off-stream storage of water of 50 000 m^3, or more.

In addition to these documents, the recently completed Water Research Commission project by Parsons *et al* (2007) describes procedures applicable to groundwater. The report has not yet been published.

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