SECTION B:
THE ARTIFICIAL RECHARGE CONCEPT, ITS APPLICATION AND POTENTIAL

B.1 WHAT IS ARTIFICIAL RECHARGE?

B.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 B.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.

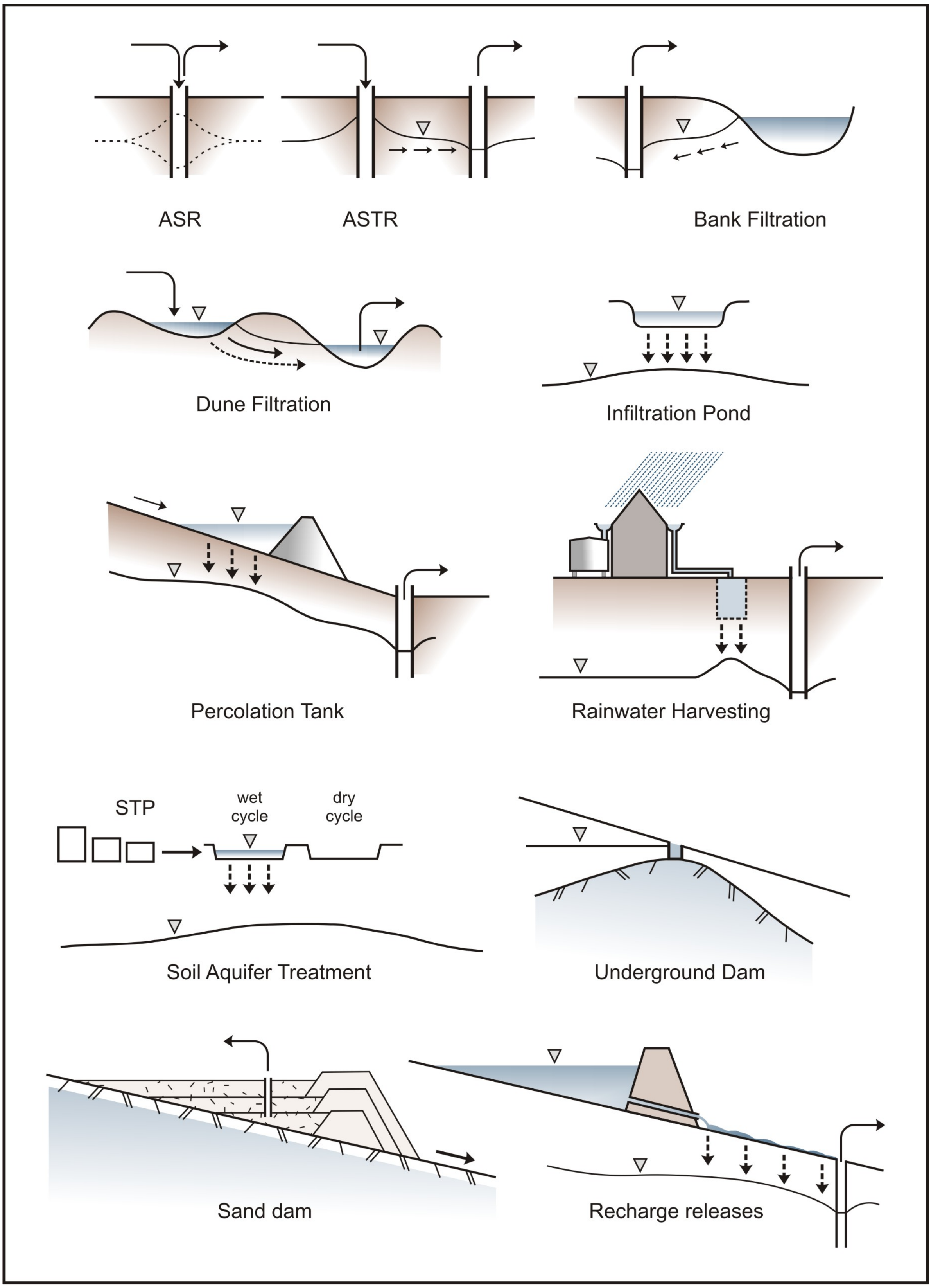


Figure B.1: Schematic of types of management of aquifer recharge

(After Dillon, 2005)

B.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. Box B.1 adapted from DWAF's Groundwater Resource Assessment II Project (DWAF, 2005) provides an overview of the storage levels in an aquifer.

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.

Box B.1: Concepts of groundwater storage

Groundwater storage can be grouped into static and dynamic storage:

Static storage *Level 1* Bottom of the aquifer

Level 2 Bottom of the natural dynamic groundwater elevation

Dynamic storage *Level 3* Current groundwater elevation

Level 4 Average groundwater elevation

Level 5 - Top of the aquifer.

A schematic representation of these levels is presented below for an elementary grid, abcd, located around the monitoring borehole, M1. The elevations of the levels 1 to 5 vary spatially. The volume bound between the layers reduced by an appropriate storage coefficient gives groundwater storage (V). The mathematical expression for groundwater storage is:

$$V = A \Delta h S$$

where A is the area of the aquifer (m^2), Δh is the thickness between any two layers of interest and S is the coefficient of storage (dimensionless).

If:

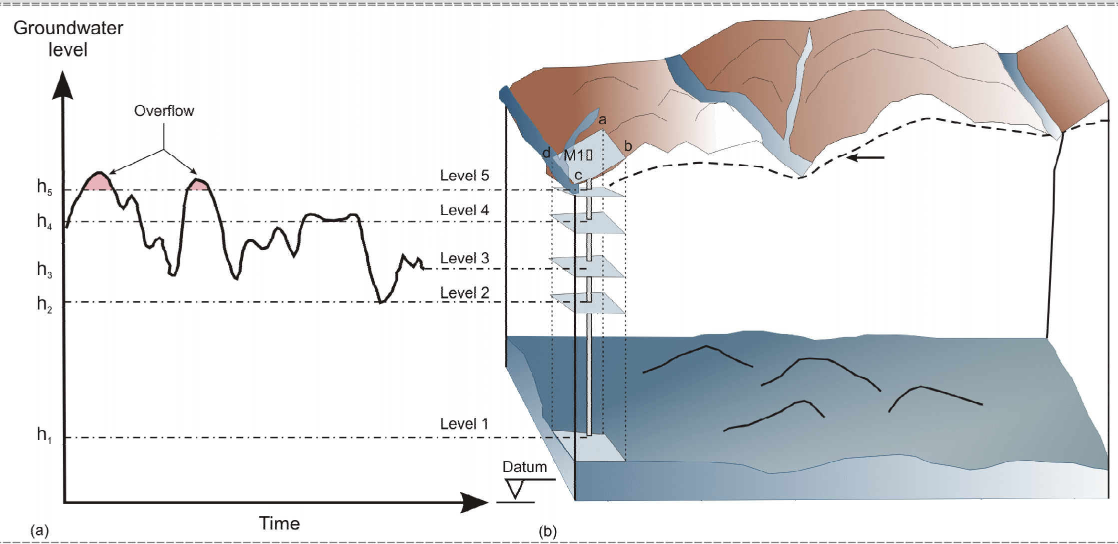
(i) $\Delta h = h_5 - h_1$, gives the maximum groundwater storage;

(ii) $\Delta h = h_4 - h_1$, gives the average total groundwater storage;

(iii) $\Delta h = h_4 - h_2$, gives the average dynamic groundwater storage;

(iv) $\Delta h = h_3 - h_2$, gives the current dynamic groundwater storage;

(v) $\Delta h = h_2 - h_1$, gives the static storage.



(a) Hydrograph of monitoring borehole M1, and (b) Schematic presentation of the physical layers

(Source: DWAF, 2005)

B.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 B.1 summarises key comparative issues of various water supply sources.

Table B.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).

B.1.3.1 Applications and benefits

Applications of artificial recharge are summarised in Table B.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 B.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

B.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).

B.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.

B.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.

B.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).

B.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.

B.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 B.3 gives an indication of the orders of magnitude depending on aquifer type and extent.

Table B.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.

B.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.

B.2 INTERNATIONAL EXPERIENCE

This section draws on international experience on the value of artificial recharge in water resource planning and management. Case studies are presented that include both site-specific examples, where artificial recharge schemes have been incorporated into the overall water management strategy for the area, town or city, and regional examples, where artificial recharge is considered on a national or regional scale as a water conservation measure.

There appears to be few official planning documents that incorporate artificial recharge within water resource management. This is probably because artificial recharge is largely considered as a localised solution to water problems and relevant documents are mostly artificial recharge feasibility studies that incorporate artificial recharge within the context of the broader water needs.

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.

Although artificial recharge is practised throughout the world, much of the literature, research and guideline documents are sourced in Europe, the USA, Israel and Australia. Countries such as India, Pakistan, Kuwait, Japan, Namibia and many others, have contributed to the international pool of knowledge in various degrees, usually, but not exclusively, with well documented case studies. Experience, lessons and future artificial recharge plans from a few countries are described below to highlight points of relevance to South Africa.

B.2.1 ASR in the USA

B.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 B.2).

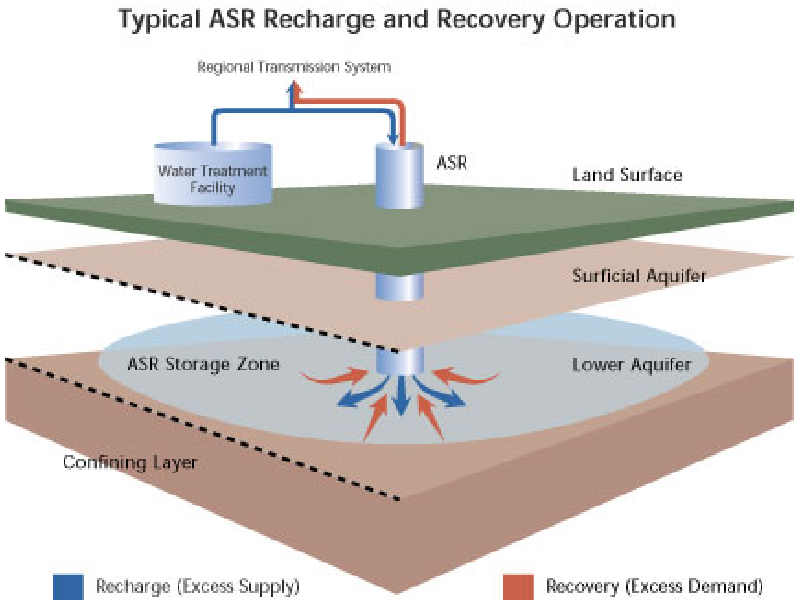


Figure B.2: Typical ASR recharge, storage and recovery operation

(Source: www.regionalwater.org)

There has been a noticeable increase in the number of ASR schemes during the past 20 years (Figure B.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.

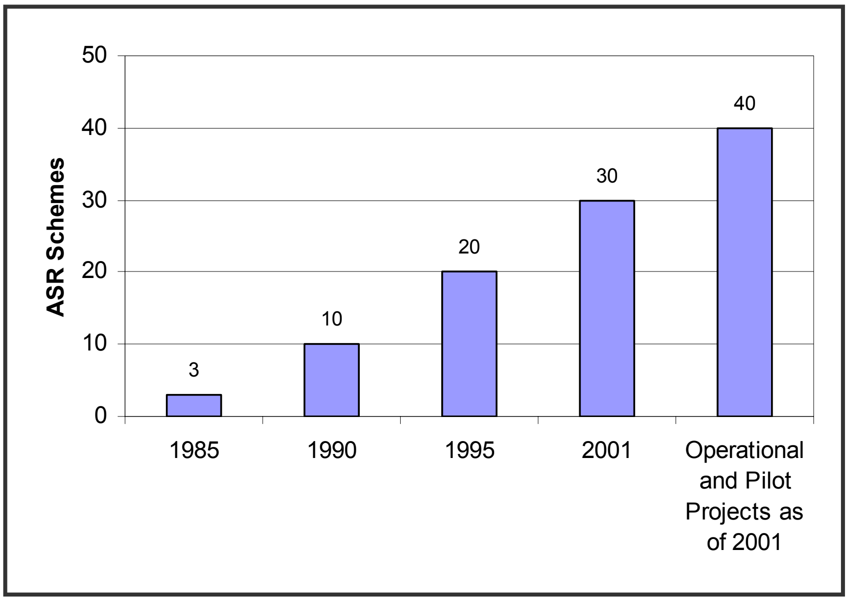


Figure B.3: Historical development of ASR schemes in the USA

(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 B.4) and for seasonal storage (Figure B.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.

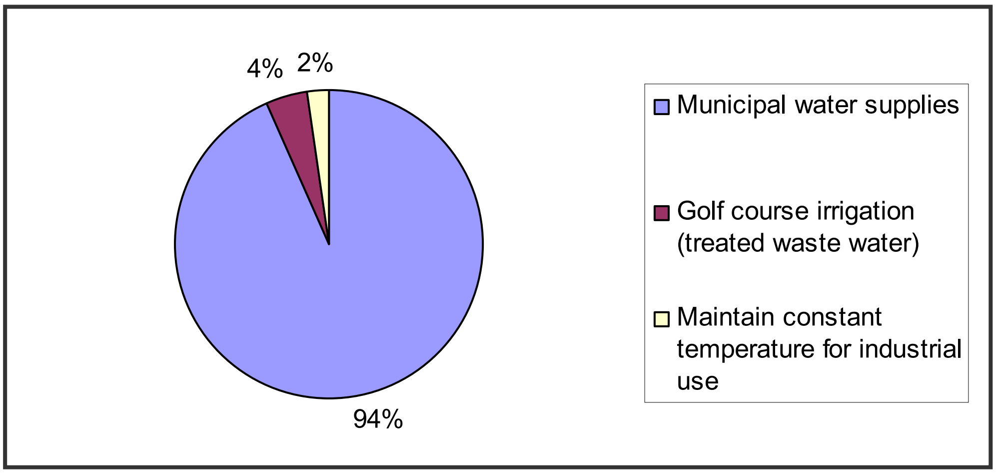


Figure B.4: Uses of ASR schemes

(Source: AWWA, 2002)

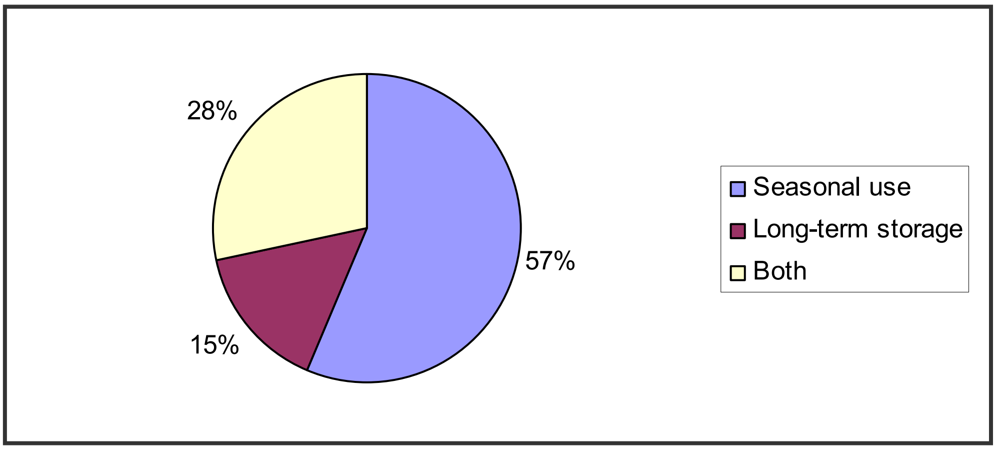


Figure B.5: Use of ASR schemes in relation to duration of storage

(Source: AWWA, 2002)

The survey indicated that, in most cases, the water source is surface water (Figure B.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 B.7).

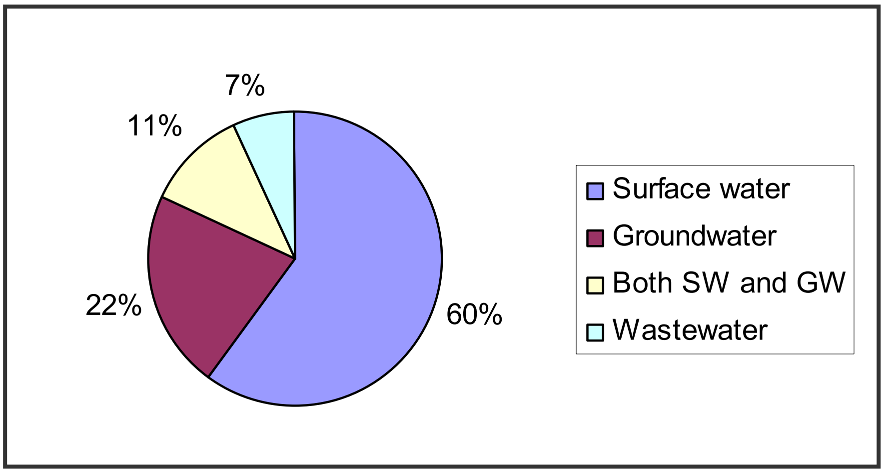


Figure B.6: Source water for ASR schemes

(Source: AWWA, 2002)

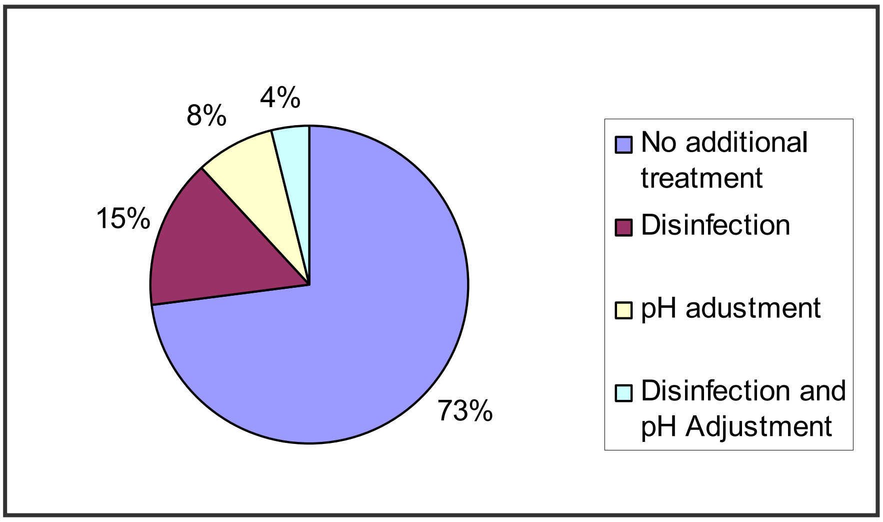


Figure B.7: Pre-injection treatment methods at potable water ASR schemes (beyond existing treatment)

(Source: AWWA, 2002)

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

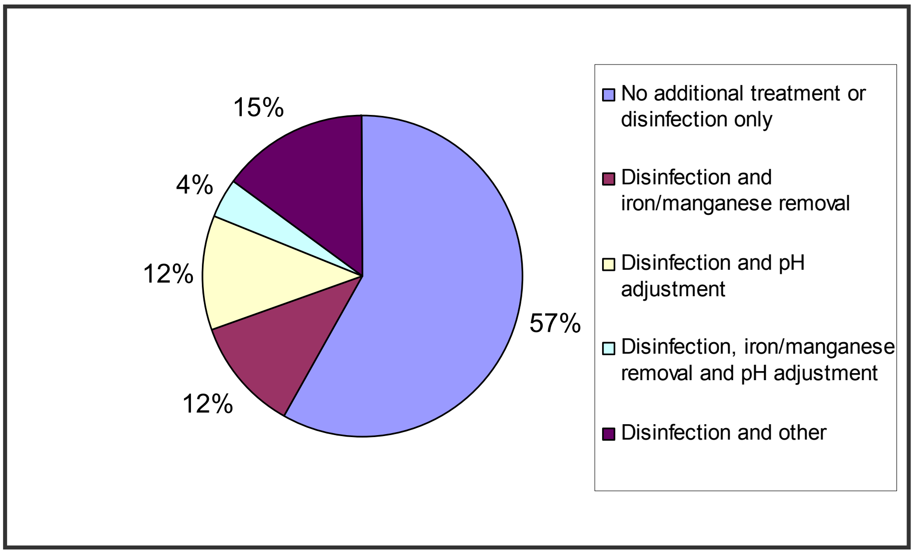


Figure B.8: Post-injection treatment methods at potable water ASR schemes

(Source: AWWA, 2002)

Sources of information:

- AWWA, 2002
- www.regionalwater.org
- D. Pyne, *personal communication*

B.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 B.9 and described in Table B.4.

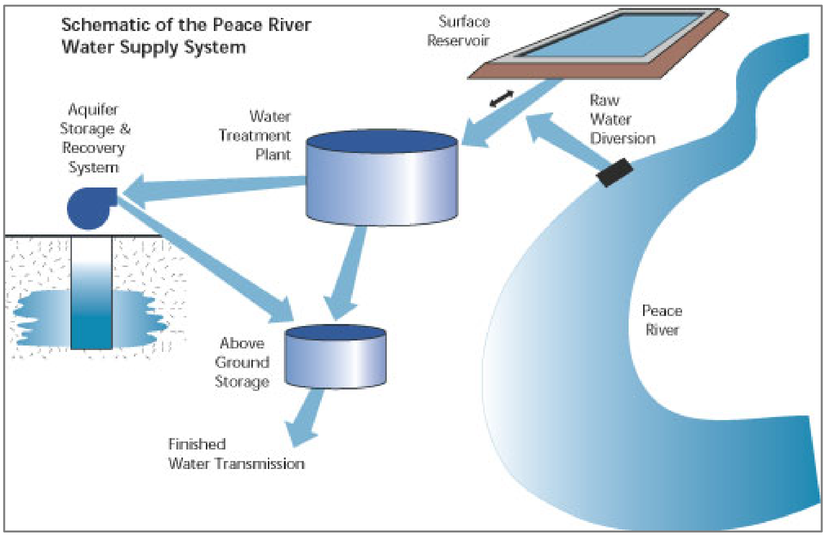


Figure B.9: Peace River Water Supply System Model
(Source: www.regionalwater.org)

Table B.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

B.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 B.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:

- Pyne, 1995
- Pyne, 2005

B.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 B.10 shows that 89 percent of ASR operators were satisfied with the ASR schemes.

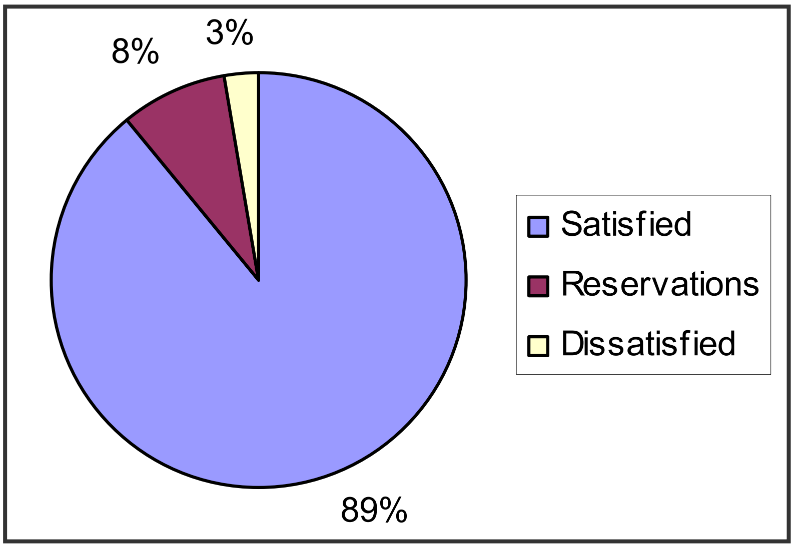


Figure B.10: Satisfaction with ASR schemes

(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

B.2.2 USA: Conjunctive Management of Surface and Ground Water in Utah

This is a very informative document on artificial recharge, and on Utah's strategies for incorporating artificial recharge into conjunctive management. Examples of topics covered are:

- Consequences of declining groundwater levels (including economic, environmental and water quality costs)
- Examples of past and present conjunctive management experiences
- Project implementation stages
- Utah Ground Water Recharge and Recovery Act

Utah has a history of investigating conjunctive management and aquifer storage and recovery (ASR) technology. Starting in 1936 and continuing intermittently to the present, numerous experiments and studies have been conducted. Conjunctive management strategies were employed in some areas simply because it made sense to do so. Despite this history only three specific projects involving managed aquifer recharge have been put into operation. This can probably be explained by over a century of steady implementation of surface water development projects. Further, conjunctive management and managed aquifer recharge require an understanding of groundwater conditions, which can be difficult.

Groundwater is out of sight, out of mind, and can be hard to define and understand. In the past, this complexity has been something of an impediment to ground water development. It is reasonable that surface water development would come first and groundwater development would come later. However, continuous development over time has brought improved pumping and underground investigation technology, expanded geologic exploration throughout the state, and the introduction of managed aquifer recharge technology. These have all made conjunctive management much easier to implement. It has also been demonstrated to be very cost effective compared to surface water development alternatives. Moreover, the possible overdraft of aquifers has created concern. Yet the demand for water increases and will continue to increase. Action today is needed to be ready for tomorrow.

Conjunctive management is a proven technology employed throughout the world, including about 70 ASR projects, with over 290 ASR wells, operating in the United States. Many more are in various stages of development. Conjunctive management strategies are among the next logical steps to more fully develop Utah's water resources.

The document concludes with two recommendations:

1) Take Immediate Action to Facilitate Conjunctive Management
2) Develop an Internet-Based, Consolidated Ground Water Information List

The details of the first recommendation have been reproduced below. This recommendation is a collection of suggested actions to be taken by leaders in cities and towns, counties, water conservancy districts and water suppliers. It includes:

- Investigate the applicability of conjunctive management strategies to increase the water supply in your location.

- Visit existing aquifer recharge sites in Utah, and surrounding states to learn from their experiences.
- Set aside lands that are uniquely situated for storing water underground. These are valuable and cannot be used after the land is put to other uses. This especially includes gravel pits located above the unconfined aquifer at the mouth of canyons. If subsequent study determines aquifer recharge cannot be accomplished, the lands can then be developed otherwise. These areas are typically well suited for temporary or permanent multiple uses such as parks and recreation.
- Investigate the status of aquifers. This includes declining ground water levels and potential contamination risks. Take action based on what is found.
- When agricultural land is converted to urban use, investigate the options of directly putting former irrigation waters into the community water supply or developing a conjunctive management project to store those waters in aquifers.
- Require new subdivisions, annexations, or additions to provide the water needed by those entities.
- Require urban developers to install storm water recharge basins with every new development.
- Flood retention reservoirs are routinely installed on mountain streams to reduce the peak runoff. Investigate and locate the aquifer recharge sections of the stream and build the flood retention reservoirs at these locations.
- Locate debris collection basins as described above for flood retention reservoirs.

Source of information:
- Utah Division of Water Resources, 2005

B.2.3 India: Master Plan for Artificial Recharge to Ground Water in India

B.2.3.1 Overview of the Master Plan

The preparation of India's Master Plan for artificial recharge to groundwater aims at providing area specific artificial recharge techniques to augment groundwater resources. It is based on the two important requirements of source water availability and the capability of aquifers to accommodate this water. The specific problems in different areas in the states, like excessive groundwater development resulting in groundwater decline, water scarcity due to inadequate recharge in arid areas, low groundwater retention in hilly areas despite substantial rainfall, urban areas with limited groundwater recharge and related problems of urban pollution, were considered in the preparation of the master plan.

To fully utilise the available surplus monsoon runoff in rural areas, the techniques emphasised include surface spreading such as percolation tanks, and sub surface techniques such as artificial recharge wells. In urban areas, hilly areas and coastal regions, the emphasis is on rain water conservation measures through roof top rainwater harvesting techniques. The Master Plan identifies areas suitable for artificial recharge and it prioritises areas where schemes should be implemented as a first priority to ameliorate the water scarcity problems.

Master Plan Summary:

Area identified for AR:	448 760 km^2
Volume to be recharged:	36 453 Mm^3
Total number of structures proposed (including roof top rain water harvesting):	3.9 million
Estimated cost:	R33 billion

The cost of implementing the Master Plan is given in more detail in Table B.6. It is recommended that this plan be implemented in a phased manner over a time period of 10 years as this would take care of availabilty of funds for implementation and it would enable the implementing agencies to review and modify the schemes based on data generated and experience gained in the initial stages.

Table B.6: Cost of implementing artificial recharge on a national scale

	Number of structures	Billion rand	Cost per structure (R)
Artificial recharge structures proposed	225,000	27	120,000
Roof top rainwater harvesting structures	3.7M	6.3	1,700
Total number of artificial recharge and water conservation structures	3.9M	33	-
Annual cost over a recommended 10-year implementation period	-	3.3/annum	-

Note: M = million (10^6); B = billion (10^9)

The contents of the Master Plan include:

1) National scenario for groundwater
2) Concepts of artificial recharge to groundwater
3) Need for artificial recharge to groundwater
4) Methodology for preparation of the master plan
5) Design of artificial recharge structures
6) Monitoring mechanism
7) State wise master plan for artificial recharge

The bulk of the Master Plan is in the last section: State wise master plan for artificial recharge. Typical items are discussed and quantified include:

- Identification of artificial recharge areas (this includes for example, mapping areas with declining trends in water levels, areas with relatively deep water levels, and areas with suitable geology for AR)
- Subsurface storage water requirements
- Source water availability
- Recharge structures
- Rooftop rainwater harvesting in urban areas
- Cost estimates

B.2.3.2 Background and the need for artificial recharge

Due to the diverse geological, climatological and topographic conditions in India, hydrogeological conditions vary considerably. Two-thirds of the country is occupied by hard rock formations and one-third by semi-consolidated sediments. By comparison, South Africa consists of about 90 percent of the less porous and permeable, hard-rock formations.

Over the past four decades, Indian government policies have encouraged the rapid development of groundwater resources, to the extent that groundwater is now considered the preferred source for irrigation, domestic and industrial water supplies. This development is a result of both the advancement of drilling and pumping technologies and the need for assured water supplies. The introduction of high yielding crops and the adoption of multi-cropping patterns of agriculture is one of the key factors underlying the need for dependable water supplies.

The number of groundwater wells and boreholes has increased from about 4 million in 1951 to more than 17 million in 1997. Consequently, the irrigation potential created from groundwater has increased from 6.5 million hectares (Mha) in 1951 to 45.73 Mha in 1997. It has, however, resulted in a significant depletion of groundwater resources, particularly in the hard rock areas covering the southern states. A total of about 200 000 km^2 of the country are over-exploited and show a continuous decline in groundwater levels. In many parts of the country, water levels have declined by more than 4 m, and this has led to the failure of wells and tubewells, shortages in water supplies, increasing pumping costs and higher energy consumption.

The unscientific development of groundwater in some coastal areas of the country has led to landward movement of the seawater-fresh water interface, resulting in the contamination of fresh water aquifers. In some areas, this interface has moved up to 6 km inland. The problems associated with this movement have been widespread and a number of tubewells have been rendered unusable. Even many shallow wells, which were previously yielding fresh water, have started to yield saline water due to seawater ingress.

In addition to its already extensive use, groundwater resources are placed under further stress during periods of drought. The preference for using this resource is not only due to declining storage levels in surface reservoirs, but also because the impact of erratic weather on groundwater resources has a delayed response.

Artificial recharge has been identified as playing a major role in water conservation in India. A number of pilot studies have been undertaken using various artificial recharge techniques and in a variety of hydrogeological environments. Both the technical viability and economic value of the schemes have been demonstrated, and this has led to a large-scale launching of artificial recharge schemes in the country. Emphasis on creating awareness among groundwater users stresses the need for conservation and augmentation of groundwater resources, and involves them in the implementation of artificial recharge schemes.

B.2.3.3 Areas suitable for artificial recharge

A number of hydrogeological environments located in various parts of the country provide scope for artificial recharge. These include:

- Various unconsolidated deposits in the valleys of the mountainous areas. These are suitable for artificially recharging groundwater by adopting various spreading techniques.
- Areas with steep slopes and fan deposits are considered favourable for slowing down the sub-surface drainage by constructing water retention structures.
- Alluvial aquifers are suitable for recharge through the construction of spreading basins and check dams in the recharge zone.
- Dolomitic environments can be favourable for both injection boreholes/wells and recharge structures such as spreading basins, check dams and percolation ponds.
- Depending upon the topography, thickness of the weathered/ fractured zones, continuity of fractures and climate, hard-rock areas are suitable for the construction of recharge structures, such as check dams, percolation tanks and injection wells and boreholes.

In addition to these areas of artificial recharge potential, roof-top rainwater harvesting is being made mandatory (by amending the building by-laws) in urban areas with groundwater levels deeper that 8 metres. This water is fed through various recharge structures to infiltrate the subsurface.

B.2.3.4 Case study: The basalts of Warud Taluka

The watershed covers an area of nearly 500 km^2 in Warud Taluka and represents a typical basaltic terrain. The area has been subjected to intensive groundwater development for the irrigation of orange orchards. This practice has led to a decline in groundwater levels of up to 0.4 m/year during the post-monsoon season. Wells in the area went dry and a number of boreholes were drilled to meet water requirements. Three percolation dams were constructed in natural depressions, and ten cement wells were constructed in stream beds.

Some 81 to 97 percent of the water collected and stored in the dams made its way into and recharged the aquifer. The remaining water was lost to evapotranspiration. Groundwater levels rose between 1 and 10 m. The rising groundwater levels not only resulted in dependable drinking water supplies from the wells, but the orange orchards were revitalised and new plantations, irrigation wells and additional greenery were established in these areas.

Sources of information:

- Central Ground Water Board, 2002
- Unpublished paper by Dr D. K. Chadha, Chairman, Central Ground Water Board, Ministry of Water Resources, India. Paper presented at a workshop at the 4th International Symposium on Artificial Recharge of Groundwater, Adelaide, Australia, 2002
- Chadha, 2002

B.2.4 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

B.2.5 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 waster 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

B.2.6 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 B.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.

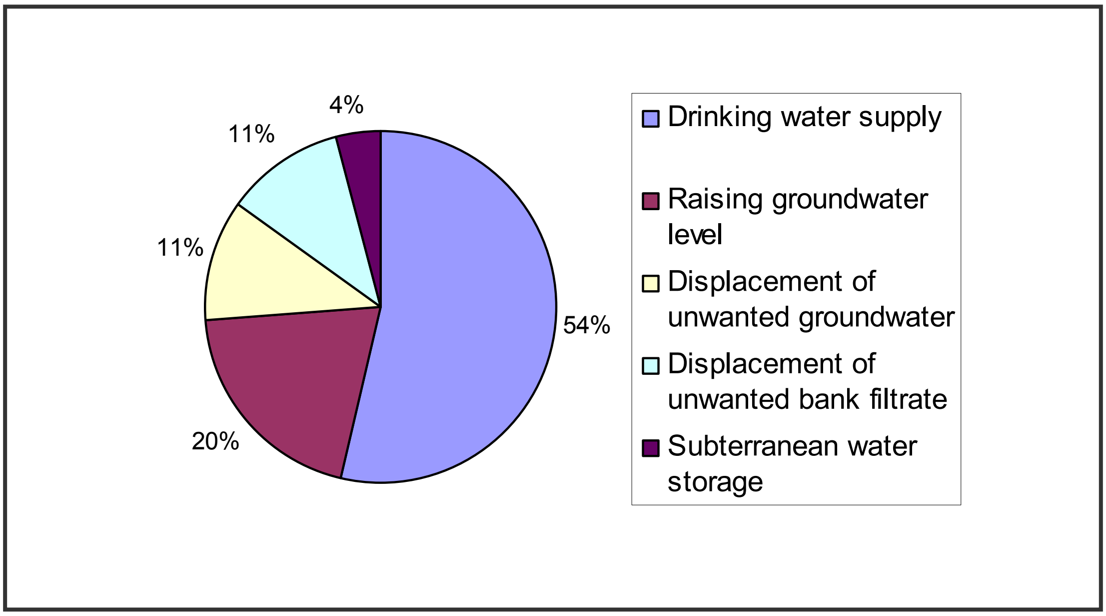


Figure B.11: Uses of artificial recharge in Germany

(Source: Schottler, 1996)

Source of information:

- Schottler, 1996

B.2.7 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

B.2.8 Palestine

Artificial recharge using stormwater and treated wastewater is considered a viable means of reducing Palestine's water deficit. Over-abstraction of groundwater in coastal aquifers has led to an increase in water salinity and seawater intrusion. In the Gaza Strip, groundwater recharge is about 98 Mm^3/a, of which 46 Mm^3/a is supplied by rainfall using direct infiltration, the balance being obtained from irrigation return flow, leakage from wastewater and brackish transboundary flow. The total amount of groundwater abstraction is 145 Mm^3/a. This results in a deficit of 47 Mm^3/a.

The effect of this over-abstraction has been a water level decline of 20 cm/a and, as a consequence, sea water intrusion and water quality deterioration. Artificial recharge is not only expected to provide 56 Mm^3 of water to offset the deficit by the year 2020 (Table B.7), but it is also considered a means to limit sea water intrusion.

Table B.7: Expected water demand and supply in Mm^3

Target Year	2000	2005	2010	2015	2020
Recharged stormwater	*10*	*12*	*13*	*15*	*18*
Recharged treated wastewater	*5*	*10*	*14*	*29*	*38*
Natural supply	99	97	79	78	77
Total supply	**114**	**119**	**106**	**122**	**133**
Municipal demand	63.1	83.9	111	147	182
Agricultural demand	91	92.2	88.3	83.6	79.7
Total demand	**154**	**176**	**200**	**230**	**262**
Total deficit	**40**	**57**	**94**	**108**	**129**

Source of information:

- El Sheikh and Hamdan, 2002

B.2.9 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.

Sources of information:

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

B.2.10 Switzerland

The cities of Zurich, Geneva and Basel rely on sophisticated artificial recharge schemes that use high quality (pre-treated) river water. Artificial recharge was motivated by declining groundwater yields, increasing demands, deteriorating groundwater quality and the need for security of supply. Recharge methods include infiltration basins, ditches and borehole injection.

Source of information:
- Connorton and McIntosh, 1994

B.2.11 United Kingdom

Pilot studies were conducted north of London in the 1890s and the 1950s, but it was not until the 1970s that permanent artificial recharge facilities using wells and boreholes were constructed. Surplus winter water from the Lee River is pre-treated to drinking water quality and injected into the aquifer. A high level of treatment is adopted so as to avoid clogging and to protect the groundwater resource.

The Lee Valley and Enfield-Haringey schemes are currently the only artificial recharge projects operating in the UK. Both make use of surplus potable mains water (derived from the Thames and Lee Rivers) that is injected into the deeply confined chalk aquifer of the London basin. When fully developed, the two schemes will provide a strategic drought resource of 60 Mm^3/a for the London area that has a current water deficit of 10 percent.
Feasibility studies to develop similar artificial recharge schemes have been undertaken in south London, and projects in the Anglia, Severn-Trent and Yorkshire regions are in the planning stage. All artificial recharge schemes require approval from the National Rivers Authority which regulates abstraction licences and consents to recharge (quantity and quality) into aquifers.

Source of information:
- Connorton and McIntosh, 1994

B.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 B.8 and Figure B.12.

In addition to the artificial recharge sites listed below, feasibility studies are being conducted in three other areas, namely Langebaan, Plettenberg Bay and Prince Albert. These are briefly described after descriptions of the operational sites.

Table B.8: 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
Calvinia	Recently tested
Sand dams, Namibia, etc.	Up to 50 years

Figure B.12: Southern Africa's artificial recharge sites

B.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 B.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 B.9: 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.
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 1.5×10^6 to 2.5×10^6 m^3/a (main basin only)
Recharge rate/volume as percent of current requirement	25 – 40 %
Proportion of water	At least 40 %

Town	ATLANTIS
conserved through AR	
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

B.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.

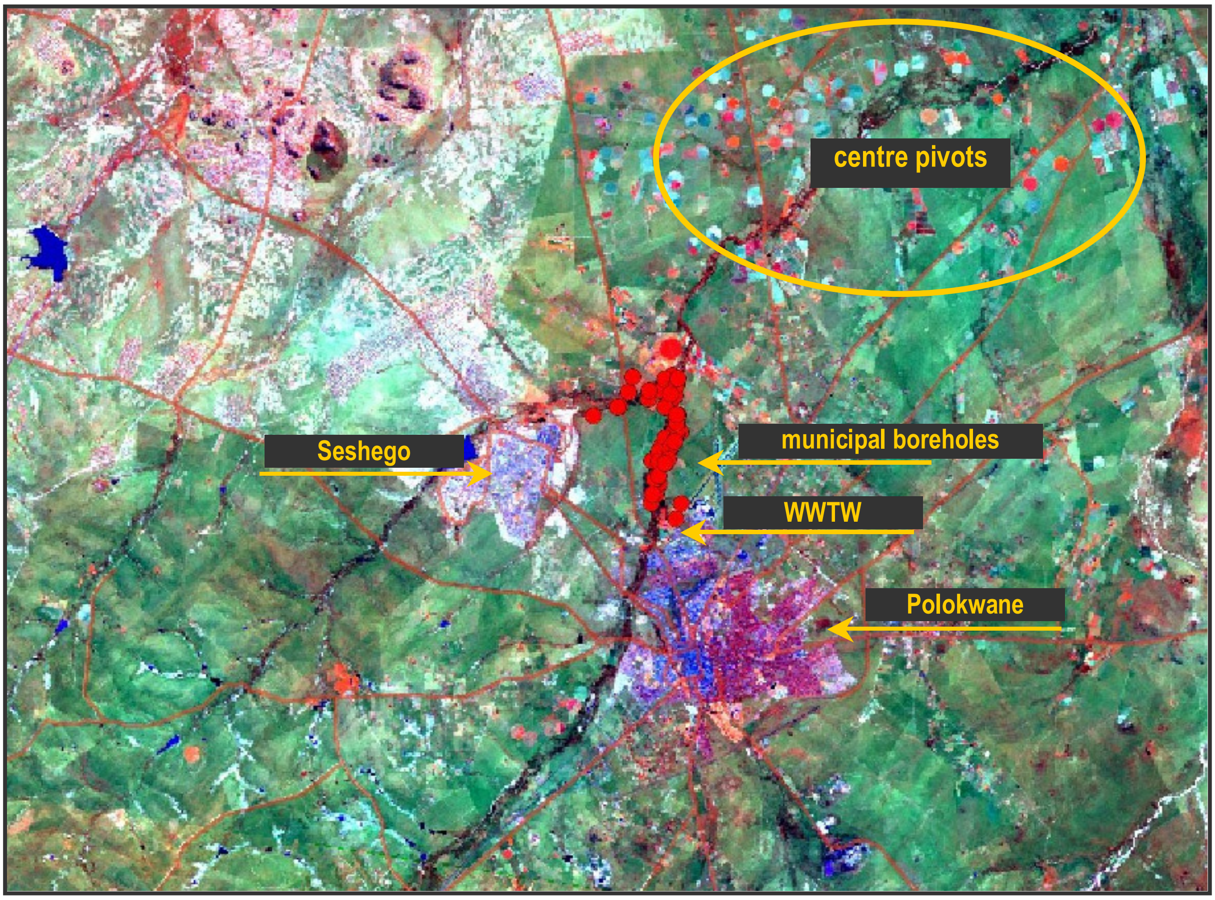


Figure B.14: Satellite image showing large-scale centre-pivot irrigation down-stream from the Polokwane Waste Water Treatment Works (This water is abstracted from the hard-rock aquifer that is recharged with waste water)

Table B.10: 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.

Source of information:

- Murray and Tredoux, 2002

B.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 B.15: Infiltration basins at Omdel

Table B.11: 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: $18x10^6m^3$

Town	WALVIS BAY, SWAKOPMUND, HENTIES BAY, RÖSSING MINE
	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

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

Table B.12: 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

B.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 B.17.

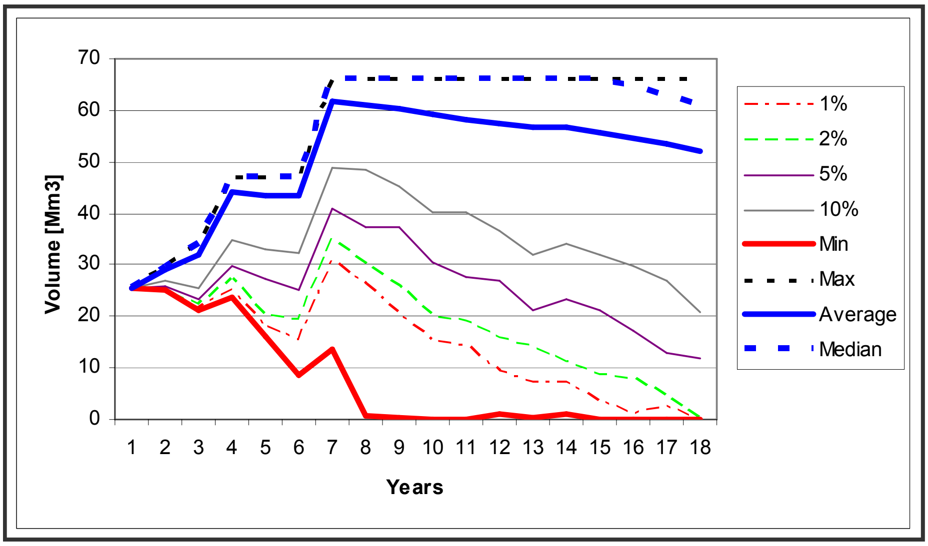


Figure B.17: Probabilities of the volume of storage in the aquifer

(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 B.13.

Table B.13: 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.

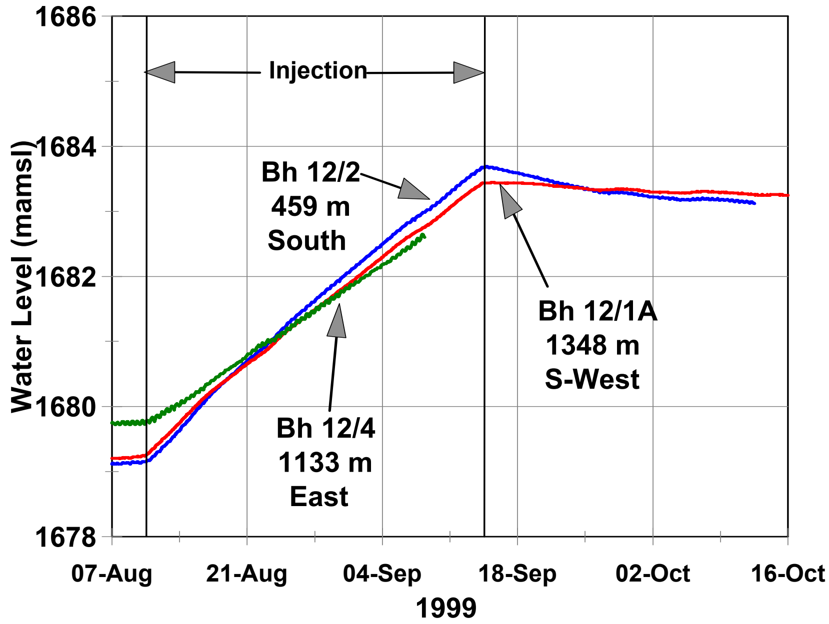


Figure B.18: Windhoek, the rise in groundwater level due to borehole injection (Observation borehole number, location and distance from the injection borehole is indicated)

(Source: Murray & Tredoux, 2002)

Table B.14: 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	Current: 10% Planned: 40%

Town	WINDHOEK
requirement	
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

Town	WINDHOEK
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

B.3.6 Calvinia: Dam water recharge and storage for emergency supplies

The Calvinia artificial recharge scheme provides a back-up source for emergency situations in droughts. Treated surface water from the Karee dam is stored in a highly mineralised and permeable sub-surface compartment (similar in shape to Kimberlite pipes). The stored water cannot be lost, since the permeability of the surrounding formations is very low and only the municipality has an abstraction borehole that penetrates the aquifer. Because of the mineralised nature of the host rock, the recharged and abstracted water is unfit for human consumption and needs to be blended with the dam water prior to consumption. A similar water quality problem would result from storing fresh water in certain disused mines.

Figure B.19: Injection and abstraction boreholes in Calvinia

Table B.15: Key features of the Calvinia artificial recharge scheme

Town	**CALVINIA**
Population	8 500
Water requirements	~0.4 Mm^3/a
Town's water sources	Dam and groundwater
Water source for AR	Treated dam water
Purpose of AR	Water banking for emergency, drought supplies
Type of aquifer	Fractured, cylindrical, breccia pipe
Type of AR	Borehole injection
First AR activity	2001 (1st injection run)
Recharge rate/volume	7 L/s; Maximum storage potential ~80 000 m^3
Recharge rate/volume as percent of current requirement	Calvinia uses ~40 000 m^3/month during summer. The artificial recharge scheme could provide 2 months' emergency supply during the critical summer months. The town's annual use is ~400 000 m^3 (i.e. 20% of this can be stored using artificial recharge in the one equipped breccia pipe)
Proportion of water conserved through AR	It is difficult to quantify the volume of conserved water. The volume conserved would equal the volume stored in the sub-surface if the dam dried up. It is more useful to view this in terms of the value of security of supply that the artificial recharge back-up system provides, should there be a water shortage.
Quality of water source	pH: 7; EC: 20 mS/m; F: 0.1 mg/L; As: <0.001 mg/L.
Quality of water abstracted from the aquifer	Without AR: pH: 10; EC: 90 mS/m; F: 10.6 mg/L; As: 0.3 mg/L. With AR: pH: 9; EC: 95 mS/m; F: 7 mg/L; As: 0.4 mg/L.
Comments on the scheme	The scheme provides a valuable back-up emergency supply that can provide two months supply for the town. However, because the sub-surface medium is highly mineralised, the quality of the natural and recharged/stored water is unsuitable for human consumption unless blended with dam water at a ratio of at least 1:8. A similar water quality problem to this would result from storing fresh water in certain disused mines.
Key lessons	1. With 1-3 artificial recharge boreholes, it is possible to have a marked impact on the security of a small town's water supplies 2. Storage of fresh water in mineralised aquifers (and mines) can result in significant water quality deterioration 3. It is not always possible to predict the final water quality through laboratory analyses and modelling.

Source of information:
- Murray and Tredoux, 2002

B.3.7 Sand storage dams: Artificial aquifers created in river beds (Namibia)

In the more arid parts of the subcontinent, farmers are largely dependent on groundwater, and the more enterprising farmers have considered ways and means to extend their water supplies. Constructing dams in riverbeds above boreholes have largely solved this problem. However, the dams silted up quickly and, in view of the excessive evaporation, the idea originated that a dam filled with sand, that is, a "sand storage dam", could serve as a reservoir from which little or no evaporation would occur.

Wipplinger (1953) made an extensive study of the subsurface storage of water in such artificial sand aquifers in Namibia, and particularly the construction and efficiency of such systems to serve as water supply sources (see Figure B.20). His early work can have an important bearing on the use of artificial recharge as a means to reach sustainability in community water supply. Presently, extensive efforts are underway in Kenya to promote the building of sand dams for the subsurface storage of floodwater for drinking water supply, livestock watering, and sometimes agriculture (Mutiso, 2003). The Kenya initiative is supported by the World Bank.

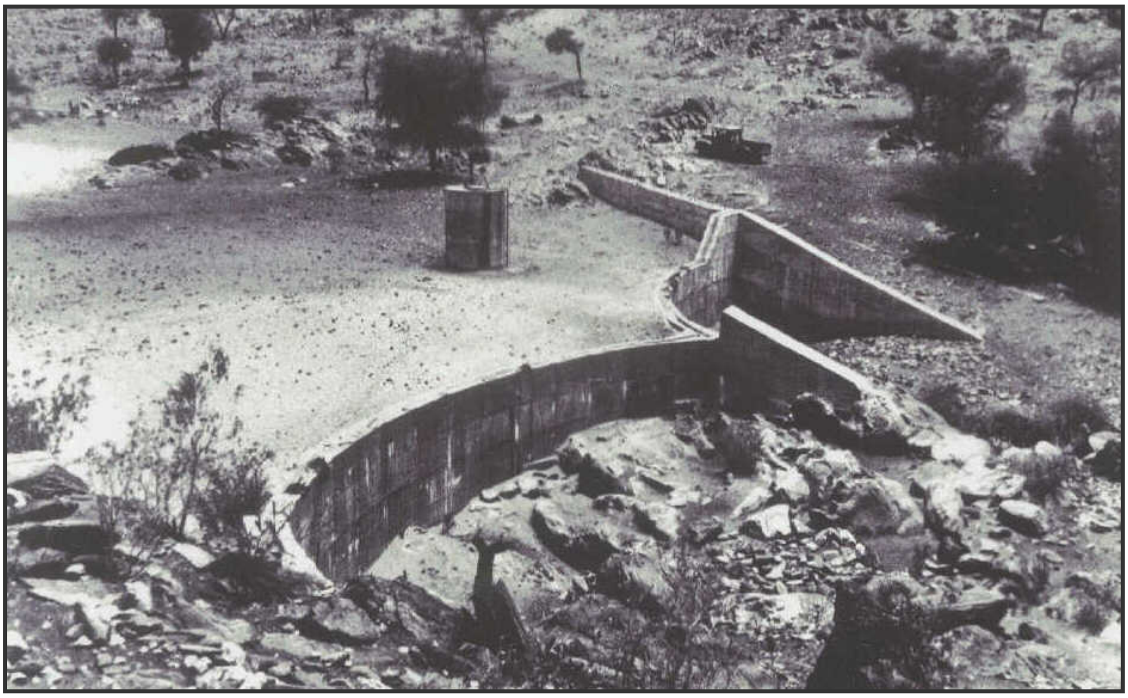


Figure B.20: Sand storage dam, Namibia

(Photo: Wipplinger, 1953)

The three case studies described below are currently being investigated to establish whether artificial recharge is a viable option to augment existing water supplies.

B.3.8 Langebaan: Is borehole injection feasible in a confined sandy aquifer?

The West Coast District Municipality gets its water supply from the Berg River and the Langebaan Road Aquifer. With increasing industrialisation at the strategic port of Saldana Bay, and the rapidly growing holiday and residential status of Langebaan lagoon area, the water supplies to these areas have become stretched to the point where additional supplies are necessary. Recharging the over utilised Langebaan Road Aquifer is currently being investigated.

Table B.16: Key features of the Langebaan Artificial Recharge Feasibility Study

Town	**WEST COAST DISTRICT MUNICIPALITY**
Water requirements	45 000 – 52 000 m^3/d in summer; 30 000 – 35 000 m^3/d winter
Town's water sources	Berg River and groundwater (4 boreholes)
Water source for AR	Treated water from the Berg River
Purpose of AR	Aquifer protection against mining of resource
Type of aquifer	Confined, primary
Type of AR	Borehole injection
First AR activity	2007 (1st pilot injection test)
Recharge rate/volume	Target recharge rate: 4000 m^3/day. Target recharge volume: 0.36 Mm^3/annum.
Recharge rate/volume as percent of current requirement	Approximately 3 months supply, i.e. 25%
Proportion of water conserved through AR	Surface runoff not artificially recharged would otherwise flow into the Altantic Ocean if not pumped for treatment for direct supply.
Quality of water source	EC: ~25 mS/m DOC: ~3 mg/L
Quality of water abstracted from the aquifer	Without AR: EC: 65 mS/m With AR: EC: 60 mS/m (target)
Comments on the scheme	The key technical factor affecting the viability of this scheme is whether the quality of the injection and aquifer waters are compatible. Microbiological and geochemical studies are being carried out to establish pre-treatment requirements to address this concern.
Key lessons	Future key lessons will be drawn from the authorisation process, the feasibility study and if commissioned, the operation and management of the scheme.

B.3.9 Plettenberg Bay: Can natural subsurface storage be used to augment the summer peak demand?

Every summer the holiday town of Plettenberg Bay on the south coast of South Africa experiences a huge inflow of people and the water use increases from about 200 000 m^3/month to over 300 000 m^3/month. Artificial recharge is being considered as one of the means to augment the summer supplies. The suburb in which existing boreholes are located requires an additional 48 000 m^3 to meet its summer requirements, and the initial aim of the project is to establish whether artificial recharge can meet this need. The source water is surplus winter surface water that will be treated prior to borehole injection. If this is a viable option, the next step will be to establish the full capacity of the artificial recharge scheme, as it may be possible to meet a far greater portion of the the summer requirements by applying artificial recharge.

Figure B.21 shows the water levels in an abstraction borehole that is being considered for recharge (prior to the installation of data loggers). During periods of high demand, the water levels are dropped by tens of metres (in 2004 the water levels are 40 m below those of 2006). If artificial recharge is a feasible, the aquifer in this area will be fully recharged on an annual basis prior to the December peak-demand period.

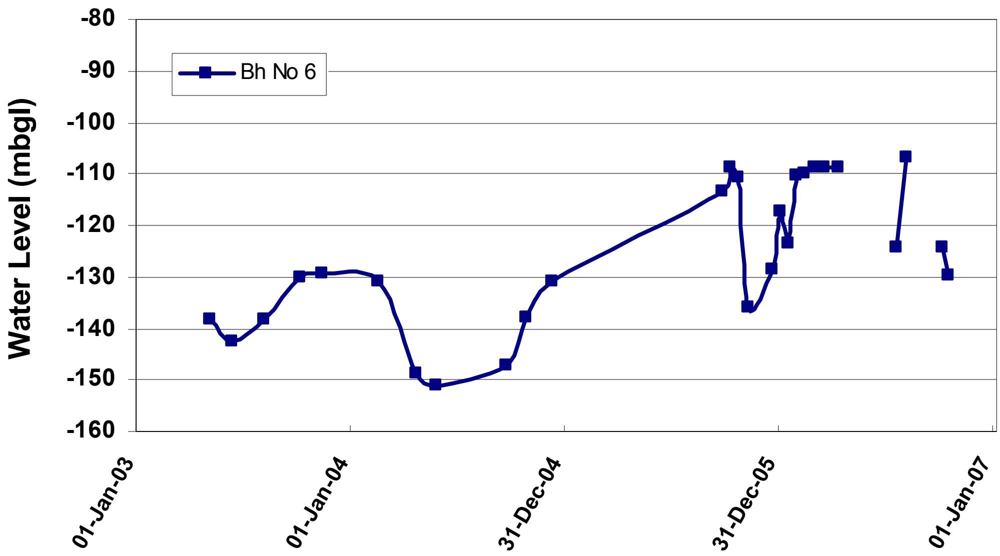


Figure B.21: Borehole water levels in Plettenberg Bay

Table B.17: Key features of the Plettenberg Bay Artificial Recharge Feasibility Study

Town	PLETTENBERG BAY
Water requirements	~3 Mm^3/a
Town's water sources	Keurbooms River and groundwater
Water source for AR	Treated river water
Purpose of AR	Augment summer peak demand
Type of aquifer	Fractures sandstones
Type of AR	Borehole injection
First AR activity	Test injection is planned for 2007
Recharge rate/volume	Planned injection rates: 10 – 20 L/s; Minimum injection volume: 50 000 m^3
Recharge rate/volume as percent of current requirement	50 000 m^3 is equivalent to 3 months of supply for the suburb in which the boreholes are located. The artificial recharge storage capacity in this area is estimated to be 750 000 m^3.
Proportion of water conserved through AR	Surface runoff not artificially recharged would otherwise flow into the Indian Ocean.
Quality of water source	pH: ~7; EC: ~10 mS/m; DOC: ~4.0 mg/L.
Quality of water abstracted from the aquifer	Without AR: pH: ~6; EC: ~120 mS/m. With AR: To be established
Comments on the scheme	The water table in the aquifer at the planned recharge site sits over 100 m below ground level. The potential for large-scale artificial recharge exists if the recharged water remains within the borehole capture zone after injection.
Key lessons	Sufficient borehole water level data was not available to rapidly establish whether artificial recharge could be a viable water augmentation option. It is recommended that as soon as an artificial recharge scheme is conceptualised, or as soon as it is identified as a water supply option), data loggers should be installed in boreholes to measure water levels and preferably EC, pH and temperature.

B.3.10 Prince Albert: Can the the aquifer be filled during the single month when surface water is available for recharge?

Prince Albert, like Plettenberg Bay experiences a large increase in water demand over summer. The daily water use increases from about 1 000 to 3 000 m^3/day, and all boreholes are used to capacity to bridge this period. A small portion of the town's water comes from an old furrow that is fed with excellent quality mountain runoff, and this is shared with local residents and farmers. Every winter, and over a four week period, the furrow is cleaned, and this provides a potential source for artificial recharge. The towns' boreholes are reasonably high yielding (~10 L/s) but natural recharge to the nothern wellfields is limited, and it is this area that hs been identified for potential artificial recharge. As with Plettenberg Bay, the intention would be to replenish the aquifer before the onset of the summer months. If the full flow of the furrow could be recharged, it would amount to ~120 000 m^3 which is equivalent to about one-and-a-half months of the summer requirements, and a welcome security system for a Karoo town.

Historical data from one of the boreholes targetted for recharge shows that water levels drop by tens of meters during high abstraction times. After the floods in the winter of 2006, the water levels rose to near-surface, showing the aquifer-full levels and the artificial recharge target. The recent installation of data loggers has shown how the water levels in certain boreholes steadily decline over the summer months.

Figure B.22: Prince Albert

Table B.18: Key features of the Prince Albert Artificial Recharge Feasibility Study

Town	**PRINCE ALBERT**
Water requirements	~0.4 Mm^3/a
Town's water sources	Groundwater and surface water from the Dorpsrivier
Water source for AR	Either treated or untreated river water (the water is sourced in the upper catchment in a nature reserve).
Purpose of AR	Augment summer peak demand
Type of aquifer	Fractures sandstones
Type of AR	Borehole injection
First AR activity	Test injection is planned for 2007
Recharge rate/volume	Planned injection rates: 10 – 20 L/s; Minimum injection volume: 50 000 m^3; Maximum injection volume: ~100 000 m^3. Injection volume will depend on individual borehole injection capacities, the aquifer's available space during the 1 month injection period; and the availability of surface water (estimated to be ~120 000 m^3 for the planned injection month).
Recharge rate/volume as percent of current requirement	The town uses ~90 000 m^3/month during the peak summer period. Artificial recharge could potentially supply one full month of the town's summer requirements (or about a quarter of the town's annual requirements).
Proportion of water conserved through AR	~120 000 m^3/a.
Quality of water source	pH: ~7; EC: ~5 mS/m; DOC: ~1 mg/L.
Quality of water abstracted from the aquifer	Without AR: pH: ~7; EC: ~60 mS/m. With AR: To be established
Comments on the scheme	Like Plettenberg Bay, borehole water levels were insufficient to establish whether artificial recharge is needed. The borehole capacities dropped significantly during summer months, and the limited data showed that water levels in certain boreholes are drawn down to pump intakes. Artificial recharge would be an effective measure to ensure the aquifers are full prior to the onset of the summer months.
Key lessons	The key lesson is the same as that of Plettenberg Bay – borehole water level and abstraction data are vital to establish whether artificial recharge is a feasible water supply option.

B.4 ARTIFICIAL RECHARGE POTENTIAL IN SOUTH AFRICA

B.4.1 Potential users and role players

Current and future role players involved in artificial recharge can be divided into institutions with responsibility for the regulation, licensing and monitoring of artificial recharge schemes and the potential users of artificial recharge schemes.

State institutions that have a role in the regulation, licensing and monitoring of artificial recharge schemes are:

- DWAF
- Catchment Management Agencies (CMA)
- Department of Environmental Affairs and Tourism (DEAT).

Users of artificial recharge schemes include:

- Water Services Institutions (WSI)
- Any institution involved in the provision of water services to households. This would include:
  - Water Services Authorities (WSA) and the following institutions that are contracted by a WSA to provide water services
  - Water Services Providers (WSP)
  - Water Services Intermediaries
  - Water Boards (WB)
- Water User Associations (WUA). A Water User Association represents the interests of a group of users. This would normally be made up of individual users and could include WSIs
- DWAF. Where DWAF is operating as a bulk water provider and where the bulk water supply includes an artificial recharge scheme.

Joint users of artificial recharge schemes: Where the supplier of water for an artificial recharge scheme is not the same institution as the user of the aquifer, special regulations need to be put in place to cover the rights of all involved parties.

B.4.2 Artificial recharge's potential role in water use

Artificial recharge can contribute to the quantity of water available for water use by providing storage for water that is normally not available or is lost. This includes:

- Storage of water intercepted from river flow to the sea
- Minimising evaporation
- Storage and final treatment of wastewater effluent (return flows).

In addition, artificial recharge can provide for emergency or reserve storage. An aquifer can be kept full and "saved" for droughts or other emergencies. This reduces the level of reserve storage that needs to be retained in surface storage dams. The uses of artificial recharge technologies are summarised in Section B.1.

B.4.3 Artificial recharge's potential role in water conservation

The National Water Conservation and Demand Management Strategy (NWCDMS) (August 2004) defines water conservation as follows:

> *"Water Conservation is the minimisation of loss or waste, care and protection of water resources and the efficient and effective use of water."*

The strategy further states that: Water Conservation (WC) should be considered as both an objective in water resource management and a strategy for Water Services Institutions (WSI).

This implies that, irrespective of the water demand management (WDM) objectives, it is necessary to have a long-term WC objective that acknowledges that South Africa is a water-scarce and water-stressed country.

The NWCDMS framework has eight objectives with linked strategic outputs defined per water sector institution. These are listed in Table B.19, together with the links to artificial recharge. The role of artificial recharge in Water Conservation is listed in Table B.20.

Table B.19: National Water Conservation/Water Demand Management Strategy framework objectives and the role of artificial recharge

Objective	Description of Objectives	Potential for AR contribution to objective	Need for AR to be included in outputs linked to objective
Objective 1	To facilitate and ensure the role of WC/WDM in achieving sustainable efficient and affordable management of water resources and water services	✓	✓
Objective 2	To contribute to the protection of the environment, ecology and water resources	✓	✓
Objective 3	To create a culture of WC/WDM within all water management and water services institutions		✓
Objective 4	To create a culture of WC/WDM for all consumers and users		✓
Objective 5	To support water management and water services institutions to implement water WC/WDM		✓
Objective 6	To promote the allocation of adequate capacity and resources by water institutions for WC/WDM		✓
Objective 7	To enable water management and water services institutions to adopt integrated planning		✓
Objective 8	To promote international co-operation and participate with other Southern African countries, particularly basin-sharing countries, in developing joint WC/WDM strategies.		✓

Table B.20: The role of artificial recharge in the spheres of water conservation

	Spheres of Water Conservation		
AR Purpose *(Refer to Section B.1 for description of each)*	**Minimisation of loss or waste**	**Care and protection of water resources**	**Efficient and effective use of water**
Seasonal storage	✓Evaporation		✓
Long-term storage (water banking)	✓Evaporation		✓
Emergency storage	✓Evaporation		✓
Enhance wellfield production		✓	✓
Restore groundwater levels		✓	✓
Reduce subsidence		✓	✓
Improve water quality		✓	✓
Prevent saltwater intrusion	✓	✓	✓
Hydraulic control of contaminant plumes		✓	
Reduce environmental effects of streamflow diversions and maintain the Reserve	✓	✓	✓
Defer expansion of water facilities			✓
Storage of treated water	✓		✓
Storage of reclaimed water	✓		✓
Utilise saline aquifers			✓
Nutrient reduction in agricultural runoff		✓	✓
Stabilise aggressive water			✓
Diurnal storage			✓
Temperature control			✓

B.4.4 Regional scale artificial recharge planning potential

B.4.4.1 Criteria for site selection

For the purpose of generating generalised national maps indicating the potential for artificial recharge, the factors listed in Table B.21 have been used.

Table B.21: Factors for identifying potential areas for artificial recharge application

Factor	Description	Comment
Hydraulic conductivity	The rate at which the aquifer can receive and supply artificially recharged water.	Intergranular aquifers and high-yielding fractured aquifers (See Section B.4.4.2).
Aquifer storage	The volume of aquifer storage available for AR.	Calculated using 50% of the available storage above the average water level, and mapped for the areas identified by hydraulic conductivity (See Section B.4.4.3).
Need	The need for artificial recharge should relate to all groundwater users, including the Reserve.	Municipal and agricultural users have been considered (See Section B.4.4.4). In Appendix 1 the AR potential is related to the total water requirements per sub-WMA.
Water source	Availability of a source water for AR.	In Appendix 1 the total local yield per sub-WMA is given.
Infrastructure	The location of major dams, water transfer infrastructure and water treatment facilities.	Major dams are mapped for each WMA in Appendix 1. Major inter basin transfers are shown in the NWRS but not captured in Appendix 1.

B.4.4.2 Aquifer type and hydraulic conductivity

The feasibility of successful artificial recharge implementation depends on numerous factors that are relevant at a local level. However, in order to provide a rough indication of suitable areas on a regional scale, areas of high hydraulic conductivity have been identified. These include the following:

- **Primary aquifers.** Primarily alluvium, coastal aquifers and localised riverbed alluvium. The zones identified as intergranular with borehole yields more than 0.5 L/s on the 1:500 000 hydrogeological maps have been used for this purpose. artificial recharge by means of surface infiltration may be appropriate in such areas.

- **Fractured and weathered aquifers with high borehole yields.** Two criteria have been used to identify these hard-rock aquifers: those with borehole yields more than 5 L/s and those with yields of more than 10 L/s. A 1 km^2 grid with borehole yields recorded in the National Groundwater Data Base (NGDB) has been used to identify the areas of high borehole yield. Those that fall into the Fractured and Weathered sections on the 1:500 000 hydrogeological maps were used to identify the prime artificial recharge areas. Artificial recharge by means of borehole injection may be appropriate in such areas.

Figure B.23 shows the areas of artificial recharge potential based on the above criteria for aquifer suitability.

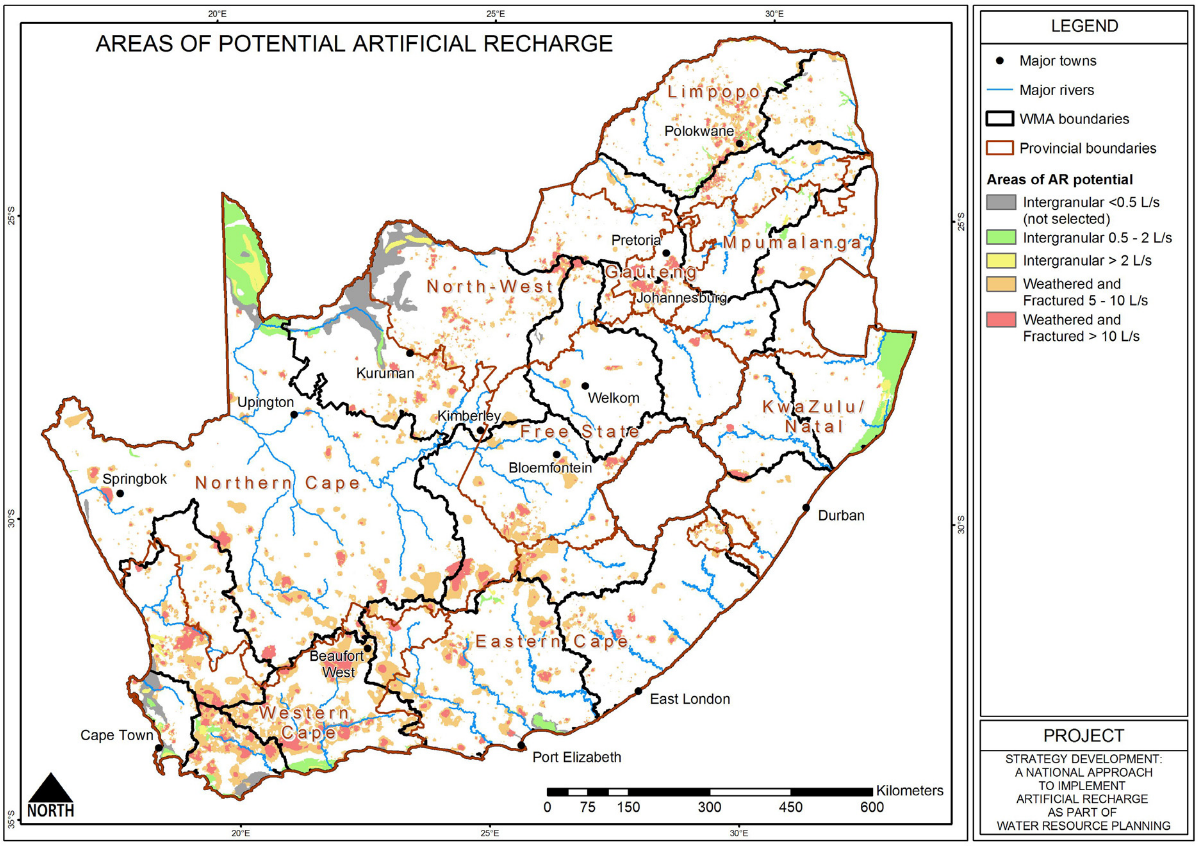


Figure B.23: Areas of artificial recharge potential based on aquifer type and areas of high hydraulic conductivity (borehole yields)

B.4.4.3 Aquifer storage

Aquifer storage available for artificial recharge has been calculated based on the approach adopted by, and the data used in, DWAF's GRA II project. Storage is obtained by multiplying: Surface area x Aquifer thickness x Coefficient of storage.

In order to obtain aquifer thickness for artificial recharge purposes, the following surfaces were calculated on a 1km^2 grid:

- Top of the aquifer (a). This level has been taken from the GRA II project, and is represented by a surface connecting the valley floors as shown in Figure B.24.

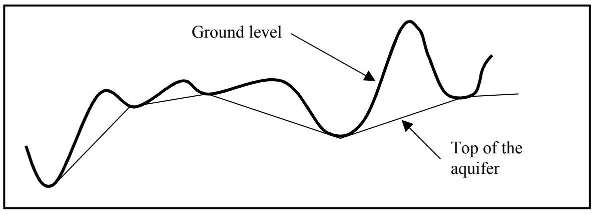


Figure B.24:Top of the aquifer

- Average water level (b). This level has been created from the NGDB recorded water levels.
- Base of weathered storage (c) has been developed under the GRA II project.
- Base of fractured storage (d) has been developed under the GRA II project.
- 5 m drawdown water level (f) – 5 m below the average water level (b)

An additional water level grid was developed, relative to these levels:

- Artificial Recharge Top level (e) is 50 percent of the difference between the average water level and the top of the aquifer.
  i.e. AR top level (e) = (b+0.5(a-b))
  Measured in metres above mean sea level (mamsl)

The values for the average specific yield of the weathered zone and the average storativity of the fractured zone used to calculate the storage volumes are based upon GRA II values for the sixty four hydrogeological regions.

Based on these water levels, the theoretical artificial recharge storage volumes have been calculated as the volume of water stored between the artificial recharge top level and the average water level.

The different aquifer and water levels used in the calculation of the artificial recharge storage volumes are illustrated in Figure B.25.

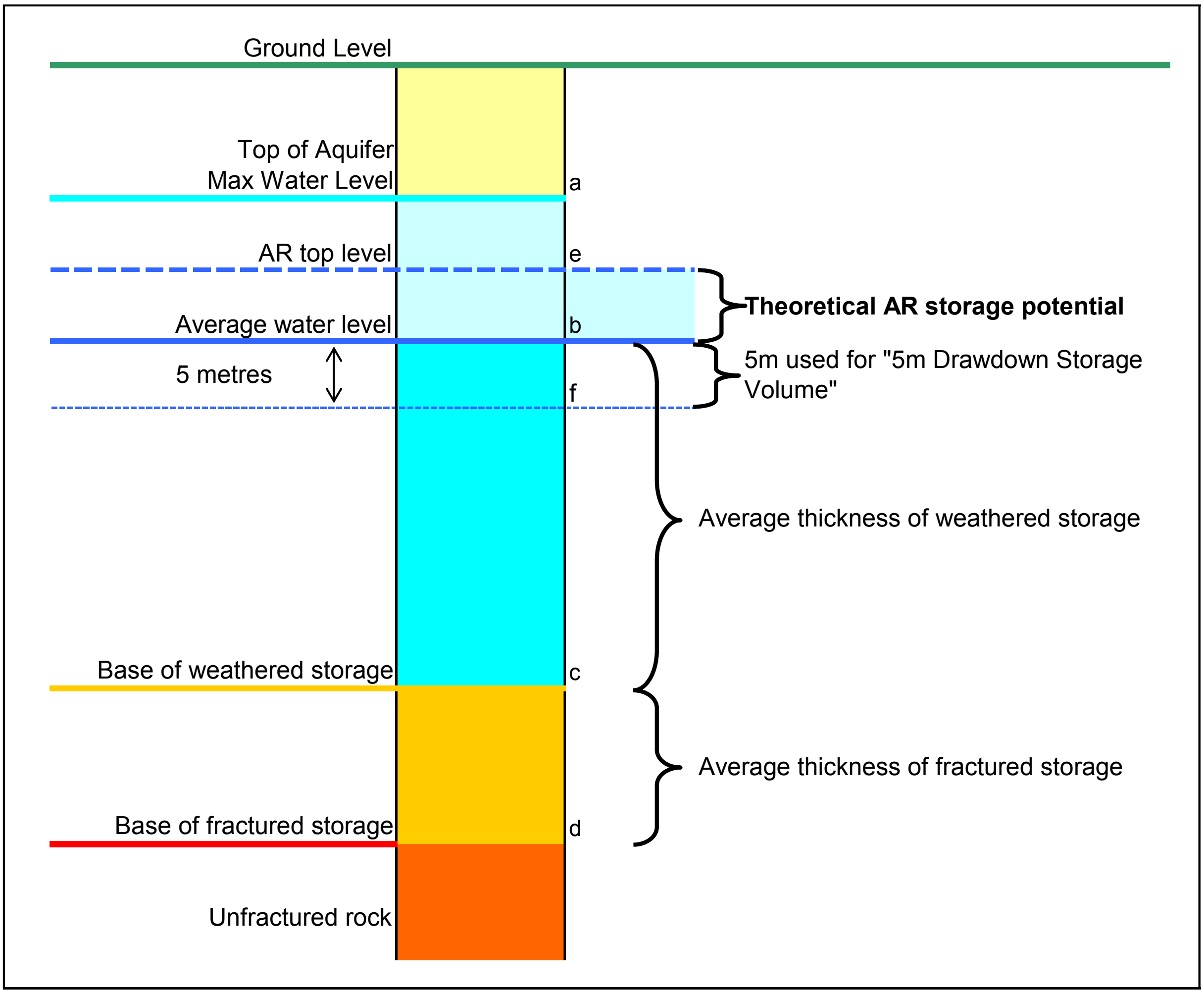


Figure B.25: Water levels and surfaces used for the calculation of artificial recharge storage potential

The calculated theoretical artificial recharge storage potential is illustrated in Figure B.26 and summarised by Water Management Area (WMA) in Table B.22.

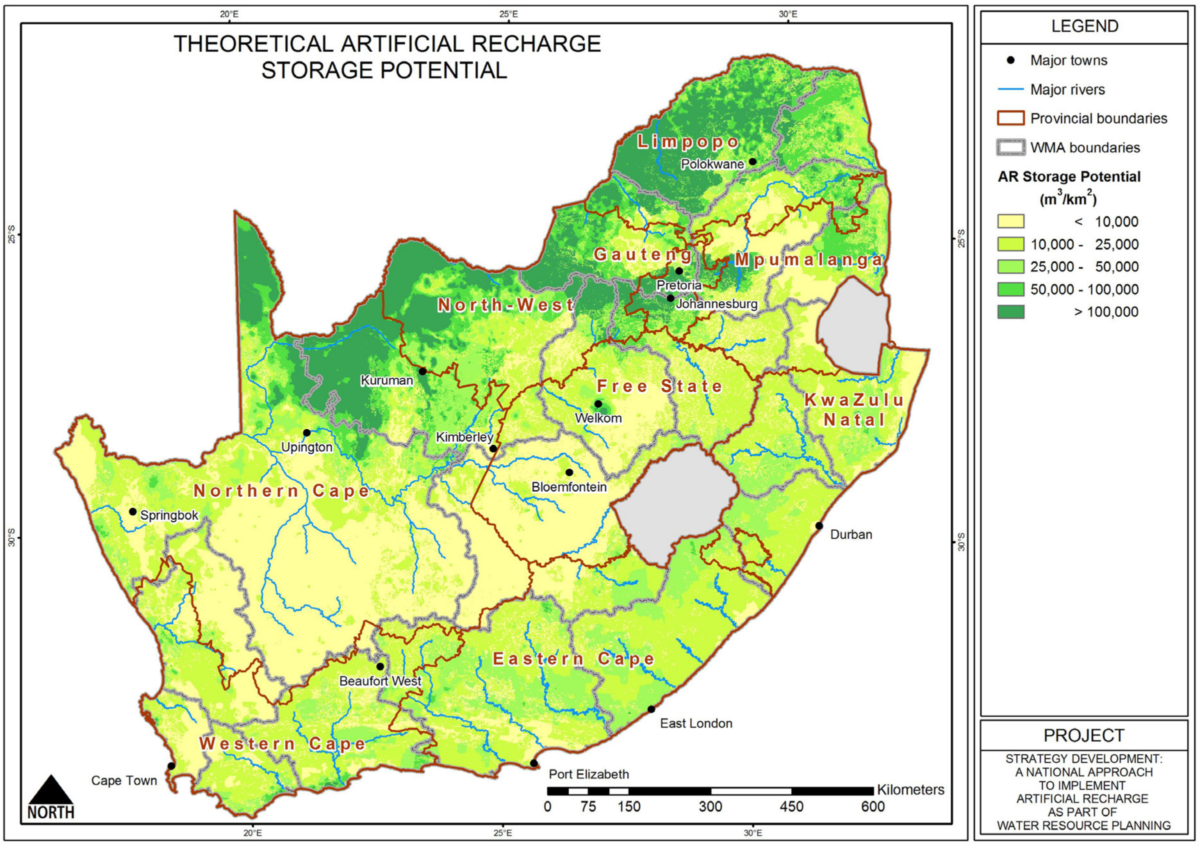


Figure B.26: Theoretical artificial recharge storage potential in m³/km²

The high groundwater storage potential shown in the northern and north-western parts of the country is explained by the fact that the data sets used from the GRA II Project placed the top of the aquifer surface far above the average water level. In many of these areas it may be unrealistic to assume that such large thicknesses are available for artificial recharge. In order to obtain more realistic storage capacities in these areas, the levels should be adjusted using localised data sets.

All areas are not suitable for artificial recharge because of aquifer hydraulic conductivity limitations. In order to reduce the country-wide storage potential to areas where artificial recharge is more likely to be feasible, the high potential areas identified in paragraph B.4.4.2 have been selected. In this way, the area is reduced to crudely accommodate hydraulic conductivity. Figure B.27 and Table B.22 are based upon the storage in this reduced area.

A more realistic quantification of artificial recharge storage potential could be made per WMA Sub-Area using detailed information for the area and by:

- Using a grid size smaller than the 1km² grid
- Re-assessing the storage layers
- Re-assessing the coefficients of storage
- Re-assessing the extent of the artificial recharge areas
- Mapping the location of water sources, existing infrastructure and areas of need.

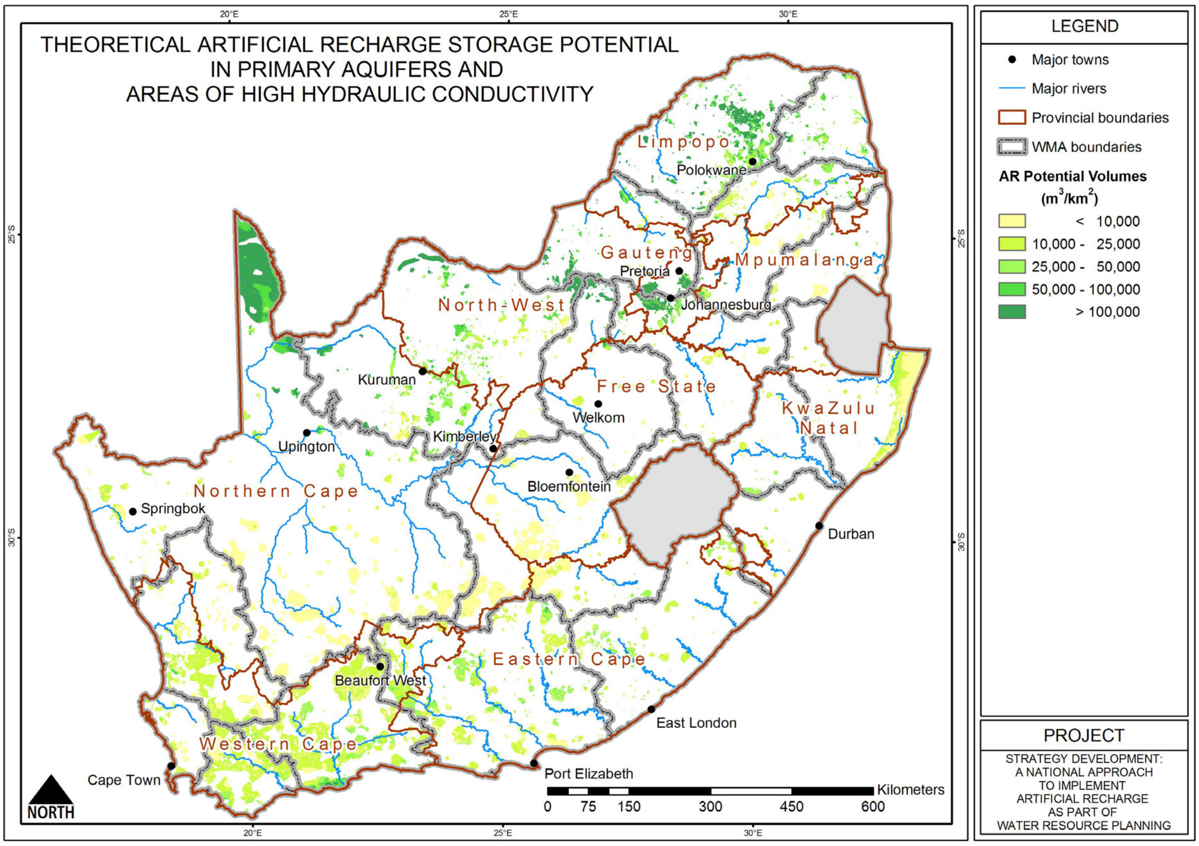


Figure B.27: Potentially favourable artificial recharge areas based on aquifer storage and hydraulic conductivity (areas of high borehole yields)

Table B.22/….

Table B.22: Theoretical potential artificial recharge storage

	Theoretical potential AR storage (million m³)			
Water Management Area	**Integranular**	**Fractured and karst areas with boreholes with yields >10l/s**	**Fractured and karst areas with boreholes with yields 5-10l/s**	**Total potential AR storage**
1. Limpopo	54	807	302	1163
2. Luvuvhu	18	98	11	127
3. Crocodile West Marico	16	486	733	1235
4. Olifants	7	114	42	163
5. Inkomati	2	14	2	17
6. Usutu-Mhlatuze	66	6	1	73
7. Thukela	0	12	15	27
8. Upper Vaal	0	259	183	441
9. Middle Vaal	0	282	199	481
10. Lower Vaal	298	566	382	1247
11. Mvoti-Umzimkulu	0	21	5	27
12. Mzimvubu-Keiskamma	0	74	24	98
13. Upper Orange	0	77	22	100
14. Lower Orange	1406	156	58	1620
15. Fish-Tsitsikamma	12	270	55	337
16. Gouritz	100	267	84	451
17. Olifants-Doorn	10	98	47	155
18. Breede	26	97	35	157
19. Berg	12	9	4	25
Total	**2027**	**3713**	**2203**	**7944**

The key factors that would influence the artificial recharge storage volumes listed above are:

- The surface area selected
- The aquifer storage coefficient
- The heterogeneity of the aquifer in terms of hydraulic conductivity and storage
- The available aquifer storage
- The relative timing of aquifer storage availability and recharge source water availability. An aquifer is only useful for artificial recharge if it can accept the water at the same time that the source water is available. The proportion of storage that is practically useable will be dependent on how the artificial recharge scheme is managed.

The theoretical artificial recharge storage potential in the identified prime areas is graphically presented per WMA in Appendix 1. The same method used to identify the prime artificial recharge areas as described in Section B.4.4.2 was used.

The GRA II project provides an estimate of the useable groundwater storage (excluding AR) by taking the volume of water stored between the average water level and the 5m drawdown water level (illustrated in Figure B.25). Five metres was selected to represent a reasonable level to which groundwater levels could be drawn down without causing the dewatering of aquifers or environmental problems. It is an aquifer management level, and for the GRA II project, was generalised over the entire country, to be 5m.

The 5m drawdown storage volume has been selected for the artificial recharge favourable areas (from Figure B.27) and is listed per WMA in Table B.23 together with the potential artificial recharge storage. Adding the 5m drawdown storage to the potential artificial recharge storage provides an estimate of the total potential useable storage in the selected high artificial recharge potential areas.

Table B.23: Natural groundwater storage and theoretical potential artificial recharge storage

Water Management Area	5m drawdown storage in AR favourable areas (million m^3)	Potential AR storage in AR favourable areas (million m^3)	Combined potential groundwater storage: AR + 5m drawdown (million m^3)
1. Limpopo	652	1163	1815
2. Luvuvhu	101	127	228
3. Crocodile West Marico	834	1235	2069
4. Olifants	138	163	301
5. Inkomati	15	17	32
6. Usutu-Mhlatuze	54	73	127
7. Thukela	15	27	42
8. Upper Vaal	323	441	764
9. Middle Vaal	454	481	935
10. Lower Vaal	845	1247	2092
11. Mvoti-Umzimkulu	12	27	39
12. Mzimvubu-Keiskamma	67	98	165
13. Upper Orange	119	100	219
14. Lower Orange	398	1620	2018
15. Fish-Tsitsikamma	249	337	586
16. Gouritz	312	451	763
17. Olifants-Doorn	104	155	259
18. Breede	100	157	257
19. Berg	42	25	67
Total	**4834**	**7944**	**12778**

B.4.4.4 Existing groundwater use

Figure B.28 to Figure B.30 illustrate current groundwater use per quaternary catchment per annum for the high artificial recharge potential areas (identified in paragraph B.4.4.2). High levels of current groundwater use can be associated with existing infrastructure for abstracting (and in future, possibly recharging) groundwater. In areas of greater groundwater use, the groundwater is more likely to be stressed and the aquifer is more likely to have available storage space, thereby increasing the possibility of implementing artificial recharge to restore groundwater levels. The GRA II data of groundwater use per quaternary catchment was used.

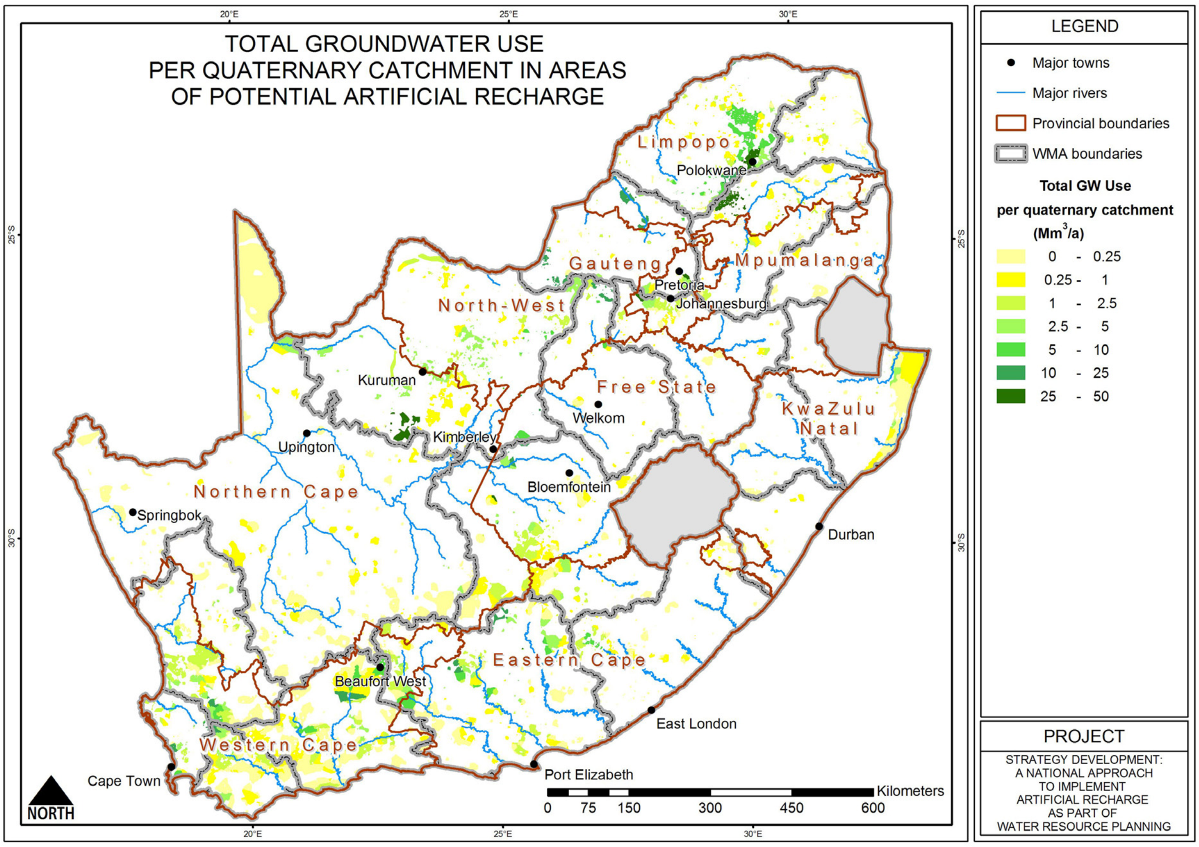


Figure B.28: Total groundwater use per quaternary catchment in areas of potential artificial recharge

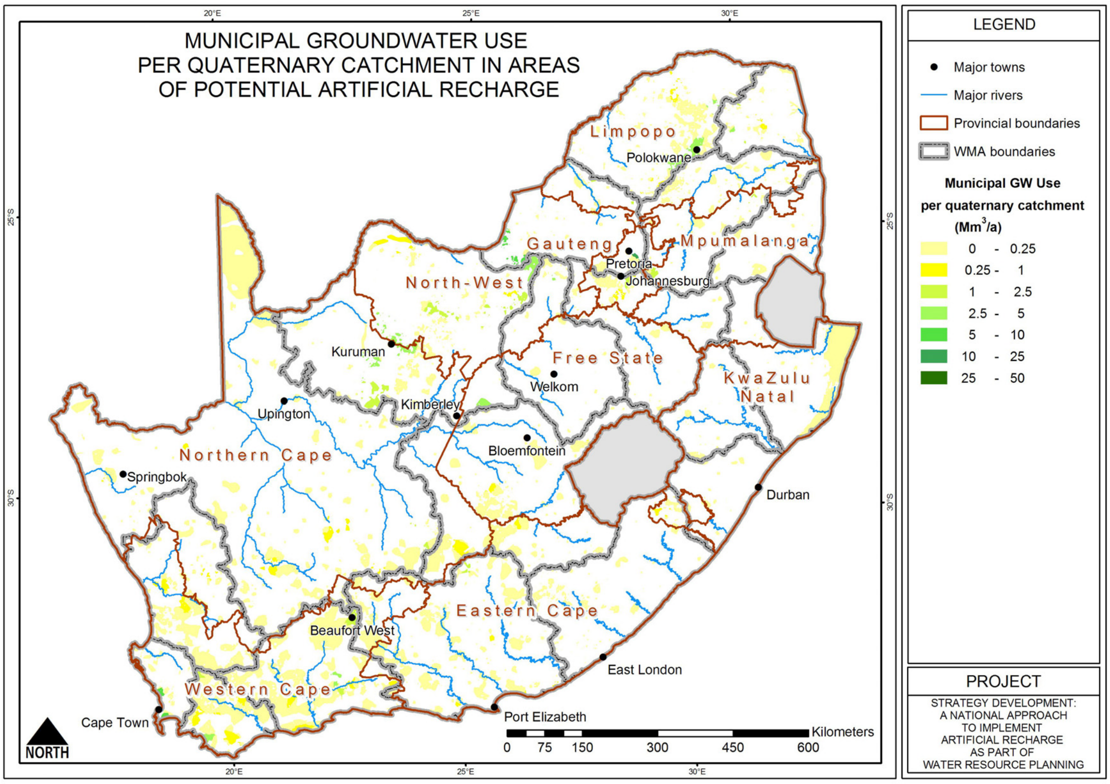


Figure B.29: Municipal groundwater use per quaternary catchment in areas of potential artificial recharge

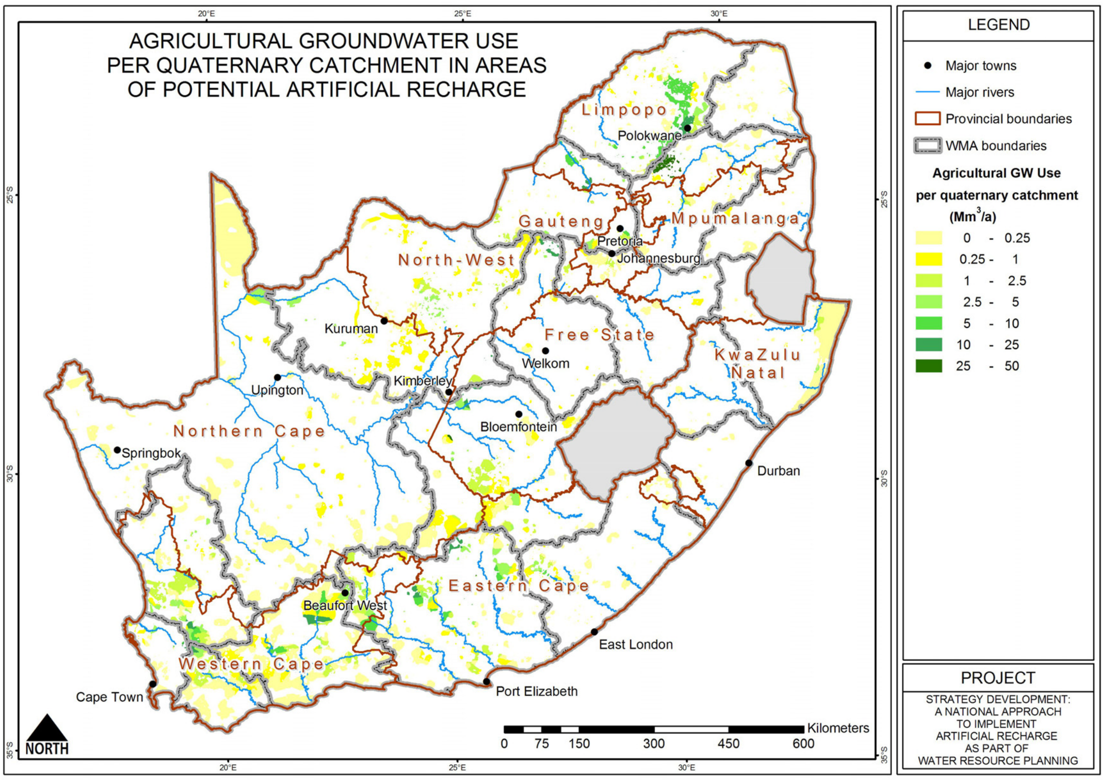


Figure B.30: Agricultural groundwater use per quaternary catchment in areas of potential artificial recharge