

Integration goes underground: A review of groundwater research in support of sustainable development in South Africa

C.Colvin*, G. Tredoux, S. Clarke, D.Le Maitre, P.Engelbrecht, A. Maherry.
[*ccolvin@csir.co.za](mailto:ccolvin@csir.co.za)

Abstract

The groundwater group of the CSIR has led groundwater research in South Africa in three critical areas during the last three decades: nitrates in groundwater; groundwater for ecosystems; and artificial storage and recovery of groundwater.

Over a third of the rural population of South Africa is dependent on groundwater resources for household and agricultural use. South Africa has some of the highest natural nitrate levels in the world (>500 mg/L N-NO₃). The group has researched the distribution of high nitrate groundwater in the Kalahari to understand why it is concentrated here. Current research is focussing on an in-situ barrier treatment to reduce nitrate levels in the water before it is pumped from the aquifer. This will help to limit the exposure of vulnerable bottle-fed infants and livestock to nitrate toxicity.

If we are to use groundwater sustainably in the future we need to understand how ecosystems rely on natural flows of groundwater to springs, rivers and wetlands. Aquifer dependent ecosystems are often important in sustaining surrounding ecosystems. The groundwater group has developed guidelines for their identification and protection within catchment management. These should help to protect rural livelihoods that depend on ADE goods and services.

Aquifers store huge volumes of water and act as nature's dams: groundwater accounts for around 95% of available, usable freshwater. This storage can be enhanced by infiltrating or pumping water into aquifers, reducing the evaporation losses experienced in surface water dams. The groundwater group has pioneered the use of artificial storage and recovery of groundwater (ASR) in the Atlantis aquifer (Cape Town) and the Windhoek aquifer (Namibia). These are the first ASR sites in Africa and are used effectively in water supply to these water-stressed areas.

1 - Introduction

South Africa is a water-scarce country and it is believed that current levels of consumptive use may be close to sustainable limits. Statistics on water use, and in particular groundwater use, are poor. It is estimated that groundwater supplies 15% of bulk water supply, around 10% of agriculture and over 50% of rural communities supplies (DWAf, 2004).

Many remote and small communities use un-treated groundwater. Groundwater quality has been the focus of a lifetime's work for Dr Tredoux. South Africa has some of the highest natural nitrate levels in the world (>500 mg/L N-NO₃). The group has researched the distribution of high nitrate groundwater in the Kalahari to understand why it is concentrated here. Current research is focussing on an in-situ barrier treatment to reduce nitrate levels in the water before it is pumped from the aquifer. This will help to limit the exposure of vulnerable bottle-fed infants and livestock to nitrate toxicity. An understanding of the nitrate problem is critical in areas where HIV-positive mothers are attempting to reduce mother-to-child transmission by bottle feeding their babies.

If we are to use groundwater sustainably in the future we need to understand how ecosystems rely on natural flows of groundwater to springs, rivers and wetlands. Aquifer dependent ecosystems are often important in sustaining surrounding ecosystems: the oasis effect. The groundwater group has looked at the wide array of groundwater-linked ecosystems in southern Africa and developed guidelines for their identification and protection within catchment management. South Africa is now positioned to take a lead in environmental allocations of groundwater.

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aquifers, reducing the evaporation losses experienced in surface water dams. The groundwater group has pioneered the use of artificial storage and recovery of groundwater (ASR) in the Atlantis aquifer (Cape Town) and the Windhoek aquifer (Namibia). These are the first ASR sites in Africa and are working effectively in support of water supply to these water-stressed areas. The Department of Water Affairs and Forestry (DWAFF) has now developed a national strategy to implement ASR across the country.

2 – Nitrates in groundwater

High nitrates in drinking water as a rule tend to be more common in groundwater supplies than in surface water supplies (Kempster, 2005). In many parts of the world nitrate occurs at significant levels in groundwater and a notable part of the population uses water with nitrate levels in excess of the WHO maximum drinking water standard (Spalding and Exner, 1993). In South Africa, high nitrate levels in groundwater is the single most important reason for groundwater sources to be declared unfit for drinking, i.e. nitrate N exceeding 10 mg/L (Marais, 1999). In 1993, Tredoux reported that hydrochemical results held by the Department of Water Affairs and Forestry (DWAFF) showed that 27 % of groundwater abstraction points (approximately 5 000) in South Africa yield groundwater with greater than 10 mg/L NO₃-N. Fifteen percent exceed 20 mg/L and 4 % exceed 50 mg/L NO₃-N.

High levels of nitrate in drinking water may cause methaemoglobinaemia or Blue Baby syndrome (WHO, 1993) and death of livestock. Although no statistics are available it is known from recorded cases that infant methaemoglobinaemia occurs in southern Africa (Super et al., 1981, Hesseling et al., 1991, Tredoux et al., 2005). In the future the risk is expected to dramatically increase as a result of efforts to contain HIV (Colvin and Genthe, 1999). The South African Department of Health advises HIV-positive mothers to bottle-feed infants to reduce the risk of mother-to-child transmission of the HIV virus via breast milk. This reduces the risk of infant mortality as a result of Aids, but exposes infants to other risks from contaminated drinking water. The overall lack of recorded information on the occurrence of

infant methaemoglobinaemia and livestock losses tends to obscure the seriousness of the situation in the developing nations.

The distribution of nitrate in groundwater has been studied in Botswana, Namibia, and South Africa. Figure 1 shows a simplified map (Tredoux et al., 2001) of areas where groundwater nitrate N exceeds 20 mg/L, i.e. twice the recommended limit of 10 mg/L set by the World Health Organization. High nitrate levels occur extensively in the northern parts of South Africa, the south-eastern parts of Botswana, and also in the south-eastern parts of Namibia. The area with high nitrate in south-eastern Namibia, at the western edge of the Kalahari Desert, links to a similar area in northern South Africa. Similarly the occurrence of high nitrate in central Namibia extends eastwards into western Botswana. A variety of lithologies and precipitation regimes are found in these areas and little agriculture is practised. One common feature of the areas is the predominance of savannah vegetation and it has been postulated that the high nitrate concentrations at a regional scale may result from native nitrogen fixing vegetation in areas with low denitrification losses (Vegter, 1995; Colvin and Conrad, 1998). Whereas the south-western Kalahari is sparsely populated, the northern parts of South Africa and the south-eastern part of Botswana have a relatively higher population density. This indicates that diverse processes or combinations of natural nitrification and pollution may be operative in the affected areas listed above.

The extreme variability of nitrate concentrations in groundwater in certain areas is noteworthy. In October 2000 approximately 200 heads of cattle died on two neighbouring farms near Ghanzi, in the Kalahari in Botswana. This prompted an investigation into the cause of death and eventually the veterinarians identified acute nitrate poisoning by contaminated groundwater. This led to an investigation of the groundwater chemistry and the potential source of nitrate. Groundwater samples of some 13 boreholes collected along the Ghanzi Ridge in October 2000 had nitrate N concentrations from 14 to 508 mg/L. Further samples from the same and other sources were collected on four occasions during the next four years and

showed variable or constant chemical compositions. In October 2000, for instance, one of the boreholes where the cattle died showed a nitrate level of 508 mg/L. From that time until November 2004 the nitrate level decreased steadily to

45 mg/L. Analysis of rainfall data for a farm near Ghanzi extending over more than 40 years confirmed that the 1999/2000 rainy season at 813 mm was nearly double the long-term mean value of 420 mm.

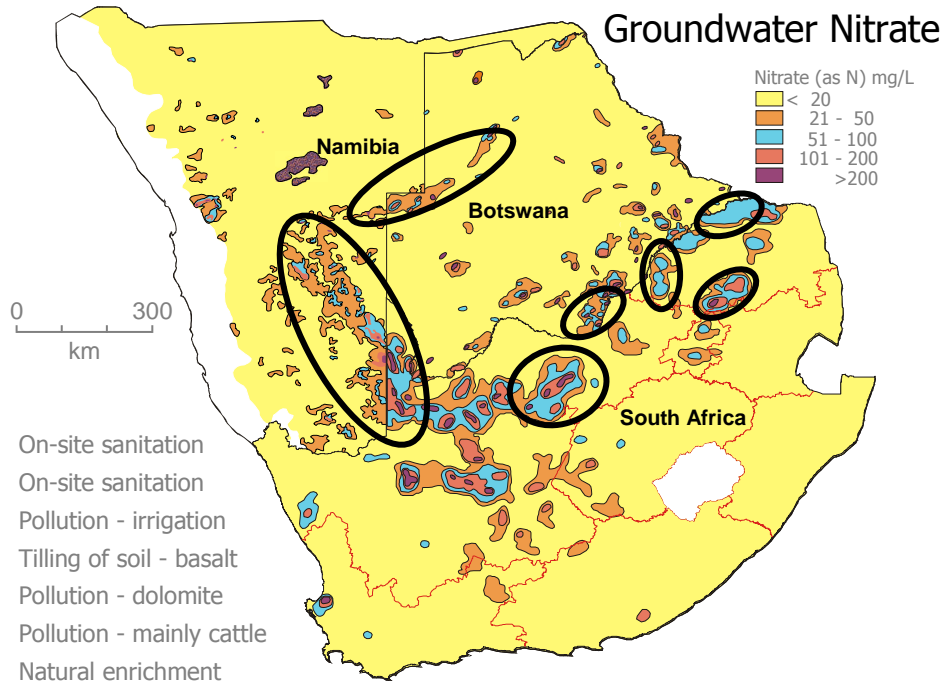


Figure 1. Location of areas of high nitrate in groundwater in the Kalahari basin and different causes of high nitrate

Tredoux and Talma (2006) used the difference between ratios of nitrogen isotopes in specific environments to discern the sources of high nitrate in environments they studied. This method indicated that in most cases, the occurrence of high nitrate in groundwater is due to contamination related to anthropogenic activities. Tredoux and Talma also found naturally high nitrate levels in geological formations such as the Ganzi group in Botswana, and its equivalent (the Nosib Group in Namibia), the Stormberg Basalt in the Springbok Flats (South Africa) and its equivalents (e.g. the Kalkrand Basalt in Namibia) and attributed it to the secondary characteristics of the geological formation and associated factors allowing the enrichment with nitrogen derived from other sources. Conclusions based on their studies with regard to sources or potential sources of nitrogen pollution include the following:

1. In unconfined aquifers, nitrate concentrations can be highly variable over short periods as they are directly affected by recharge process (rainfall, infiltration etc.) as well as nitrate polluting activity
2. Feedlots and dairy farming areas have a large potential for nitrate pollution if waste materials are not managed sufficiently. Such activities should be restricted to areas of aquifers which have impermeable layers to protect the groundwater resources.
3. Inappropriate on site sanitation at rural villages and towns frequently lead to groundwater pollution by nitrate and the abandoning of well fields.
4. Low soil organic contents in the interior of South Africa limits the occurrence of natural denitrification, hence the persistence of nitrate in semi arid and arid environments in Southern Africa.

South Africa is lagging behind countries like the USA, Canada, New Zealand, Israel and Germany in treating groundwater with high nitrate to suitable levels for various uses (Clarke et al. 2004). Proven technologies exist, but have not yet been tested in the much needed areas containing high nitrate. Current research is underway within the CSIR for various applications of denitrification technologies using slowly degradable carbon sources for denitrification. The currently operating sites range from household-scale permeable reactive barriers to industrial sites, to mining and wastewater treatment plants and municipal well fields (Robertson et al. 2003). Slowly degradable carbon sources are placed in barriers perpendicular to the flow of groundwater and such treatment occurs with a high success rate. The CSIR is building capacity in this area and testing the application of this technology to enable the safe use of groundwater in rural areas currently affected by high nitrate levels.

3 - Ensuring sustainable use of groundwater and protection of aquifer dependent ecosystems

There is significant potential to use groundwater resources to support future rural development in South Africa, however, under the National Water Act, this should be done without negatively impacting biodiversity. If we are to use groundwater sustainably in the future we need to understand how ecosystems rely on natural flows of groundwater to springs, rivers and wetlands. Aquifer dependent ecosystems are often important in sustaining surrounding ecosystems: the oasis effect. The groundwater group has looked at the wide array of groundwater-linked ecosystems in southern Africa and developed guidelines for their identification and protection within catchment management (Colvin et al, 2007; Colvin and Saayman, 2006).

Aquifer Dependent Ecosystems (ADEs) are ecosystems which require groundwater from aquifers for all or part of their life-cycle to maintain a habitat with a water budget, or water quality, that contrasts with the surrounding ecosystems (Colvin et al, 2007). ADEs occur throughout the landscape at various ecosystem scales. They are found in discharge areas of local and regional scale

aquifer systems. They are represented across the continuum of habitat types from humid aquatic systems to arid terrestrial systems, and this makes it difficult to identify their link to groundwater.

The multiplicity of types and scales of ADEs can be simplified into type-settings based on 8 principal aquifer types (based on lithology) and 7 habitat types. The type-settings describe the supporting aquifer type and ecosystem or habitat setting. Examples of known South African ADEs include: in-aquifer ecosystems in the dolomites (North West Province); springs and seeps in the TMG sandstone (Western Cape); terrestrial keystone species such as *Acacia erioloba* in the Kalahari; lakes and punctuated estuaries on the shallow sand aquifers of the east coast in KwaZulu-Natal; riparian zones in the seasonal alluvial systems of the Limpopo; seeps on the Karoo dolerite sills.

The identification of ADEs is often difficult and proving links between ADEs and aquifers often requires detailed, multi-disciplinary observation and assessment. At a coarse national scale we can identify areas with a high probability of supporting terrestrial and aquatic ADEs, as shown in figure 2. Probable vegetation classes have been identified from the National Biodiversity Initiative classification by botanists familiar with the different hydrological habitats and rooting habits of the different vegetation types (Colvin et al, 2007).

South African rivers have been classified in terms of their geomorphology, ecology, climate and geology (eg. ecoregions – Kleynhans, 2000), but they have not yet been comprehensively assessed in terms of their relation to aquifers. Licenses for use of surface or groundwater, under the new legislation, may not be issued until the quantity and quality of water required to maintain aquatic ecosystems has been determined. This water is known as the Reserve. This new legislation has stimulated research into the interconnections between rivers and aquifers. In most natural river flow systems, the low flow or baseflow is maintained by groundwater discharge from aquifers. Figure 2 shows the calculated groundwater-fed baseflow (under virgin conditions) as a percentage of total flows (DWA Groundwater Resource

Assessment (GRA)II, 2005). The GRAII calculation of groundwater-fed baseflow

took into account interflow-fed baseflow.

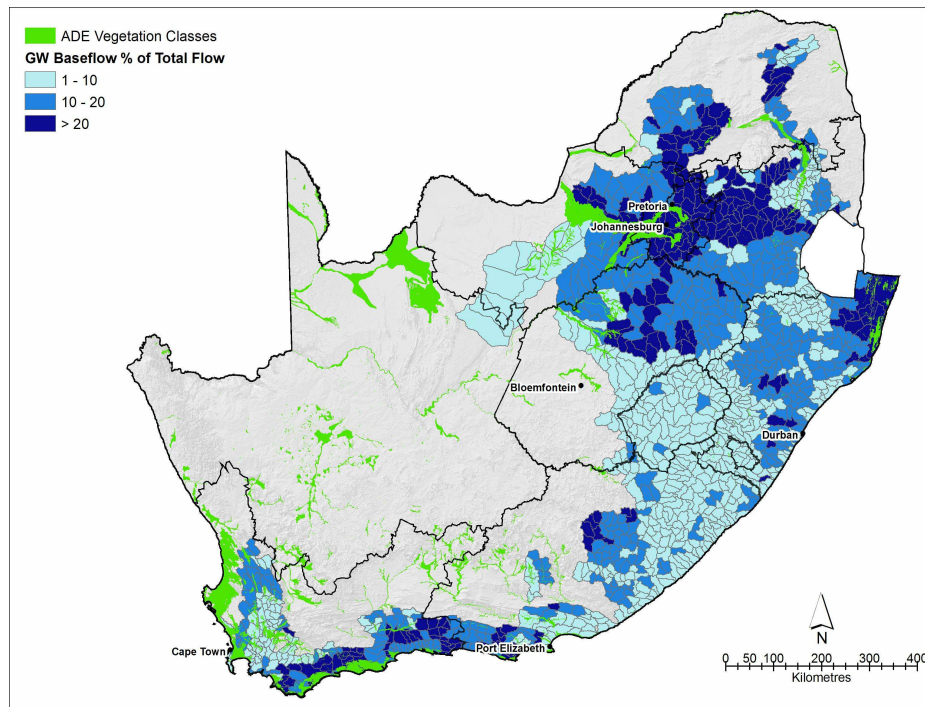


Figure 2: National scale indication of terrestrial ADEs (based on National Biodiversity Institute, NBI vegetation classes) and aquatic ADEs (based on GRAII calculated Groundwater-fed base-flow as a percentage of total flows in quaternary catchments in South Africa)

Wetlands cannot be shown at a national scale, but many in South Africa are aquifer dependent. Wetlands associated with both sinkholes (points of recharge) and springs (points of discharge) are very important aquatic features in the dolomitic karstic area of South Africa, which lacks surface water related ecosystems. Due to the relative geographical isolation of these habitats, many of the springs and wetlands sustain rare or endemic flora and fauna (Stephens et al, 2002). On the humid east coast, groundwater in the extensive coastal sands feeds lakes and wetlands in northern KwaZulu-Natal. Lake Sibiya, Lake Mzingazi and the St Lucia wetlands are examples where detailed monitoring of relative groundwater heads and lake levels and the hydrochemistry have indicated the importance of groundwater inflows (Kelbe et al, 2001). Relatively fresh groundwater discharge to these systems often maintains brackish refugia habitats during high salinity periods.

The CSIR assisted DWAF in developing a policy to enable the protection of ADEs

and sustainable management of groundwater. This operational policy recognises that:

- South African legislation (inter alia the National Water Act, National Biodiversity Act and the National Environmental Management Act) requires groundwater to be managed sustainably and the negative impacts to be minimised within acceptable limits.
- Ecosystems which are dependent on groundwater in aquifers may be impacted by groundwater abstraction and the disruption of aquifer flow regimes or groundwater contamination.
- Aquifer-dependent ecosystems (ADEs) occur in a range of habitat types and are often not recognised as being linked to groundwater. We do not fully understand the extent of ADEs, the nature of their dependency on groundwater and their consequent sensitivity to impacts on aquifers.

- Groundwater abstraction is controlled at municipal, mine, farm, village and household levels, currently with little understanding of the potential impacts on the surface environment.
- The range of legislation relevant to ADEs is diverse and responsibility resides within multiple spheres and tiers of government. Some of these responsibilities are not fully implemented and not coordinated. There is no central focus for groundwater management within DWAF HO since restructuring of the Directorate of Geohydrology.
- Lack of capacity currently constrains the implementation of government's groundwater-linked responsibilities.

The policy proposes a new Aquifer Health Programme linked to the successful River Health Programme and Working for Wetlands. Initial focus areas will include monitoring and improving our knowledge of aquifer dependency and sensitivity to change; identifying ADEs at a catchment scale; informing desktop Reserve determinations and Resource Quality Objectives linked to groundwater licensing. Figure 3 shows where ADEs are currently most at risk based on current groundwater over-abstraction and pollution risks. ADE occurrence and risk should be verified at a local scale, but the overview guides preliminary decision making about ecosystem protection and groundwater potential for abstraction.

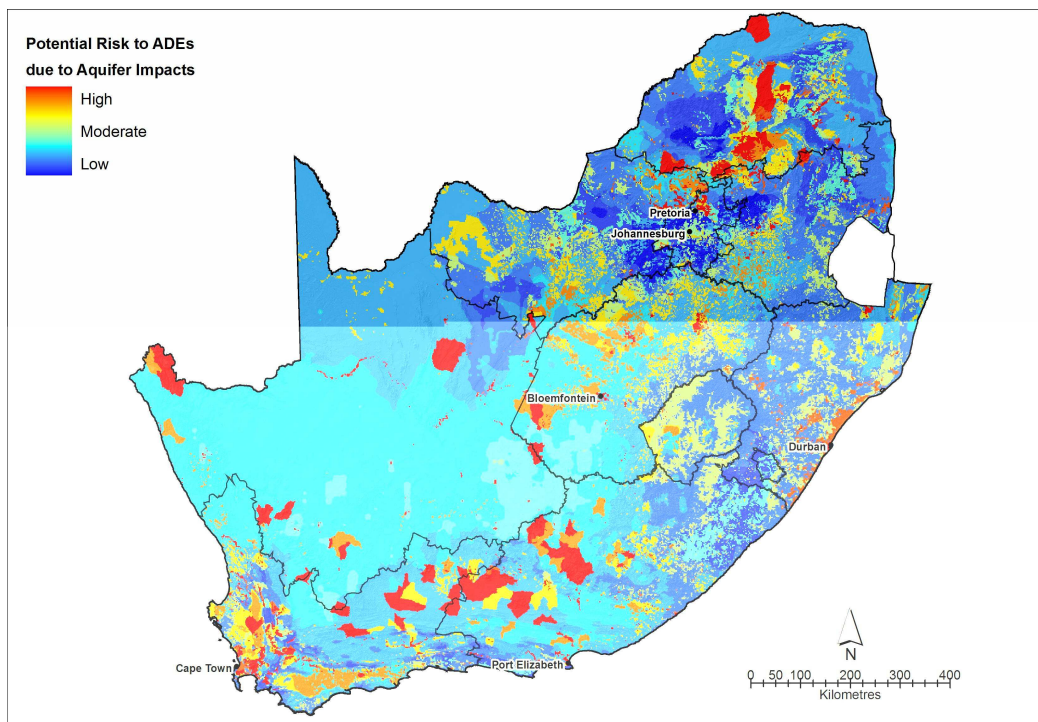


Figure 3: Potential risk to ADEs based on an assessment of aquifer vulnerability and presence of groundwater abstraction and pollution hazards at a national scale

4 - Using aquifers as storage dams

In South Africa the rate of potential evaporation is high at between 1500 mm along the cooler south coast and 3000 mm in the dry interior (Schulze et al. 1997). South Africa has a low mean annual rainfall of about 490 mm compared with a world average of about 860 mm (WRI 2000) and only 9% of this is converted to river run-off (Midgley et al. 1994). This is

far lower than the world mean value of 34% (Eamus et al, 2007), therefore the risk of water losses and contamination in surface water storage dams is significant. Aquifers are often thought of as nature's dams, with over 98% of terrestrial freshwater stored underground. People have exploited the natural storage capacity of aquifers since pre-history, and since the mid-1900s have used enhanced

or Managed Aquifer Recharge (MAR) to maximise the storage potential of aquifers.

Unused aquifer storage capacity can for the most part be developed at a significantly lower cost than surface storage facilities, and without the environmental problems frequently associated with surface storage. The overall costs of artificial recharge operations are often less than half the capital cost of conventional water supply alternatives.

Artificial recharge schemes may be considered in areas where there are surplus surface water resources at certain times of the year and available unsaturated storage with sufficient permeability for injection and recovery. Opportunities for artificial recharge should also be considered in areas where evaporative losses from open water bodies are excessively high.

A variety of artificial recharge methods are in use, involving direct recharge techniques, induced recharge and even artificial aquifers, where water is introduced to otherwise dry but permeable geological formations. Surface water spreading operations such as infiltration ponds are the most commonly used

techniques. Injection or recharge wells, where surface water is pumped directly into the aquifer, are more expensive to build and more costly to operate. Recharge water can be obtained mostly from surplus surface water, which is currently lost by means of evaporation from rivers and dams, or which flows into the sea. Possible sources are river water, water releases from dams, storm runoff and treated municipal wastewaters. Water for aquifer recharge purposes must nevertheless have a consistent high quality and a fairly predictable quantity over time.

During the 1960s Windhoek was experiencing an acute shortage of water and the CSIR was directly involved in the development of the water reclamation system at Windhoek, which came into operation towards the end of 1968. In the 1970s the CSIR and Israel collaborated closely on this topic and pilot-scale artificial groundwater recharge of treated wastewater in the Cape Flats, Cape Town, towards the end of the 1970s took place in parallel to the Dan Region Project of water recycling at Tel Aviv. The studies in the Cape Flats paved the way for the Atlantis artificial recharge project which started in 1980.

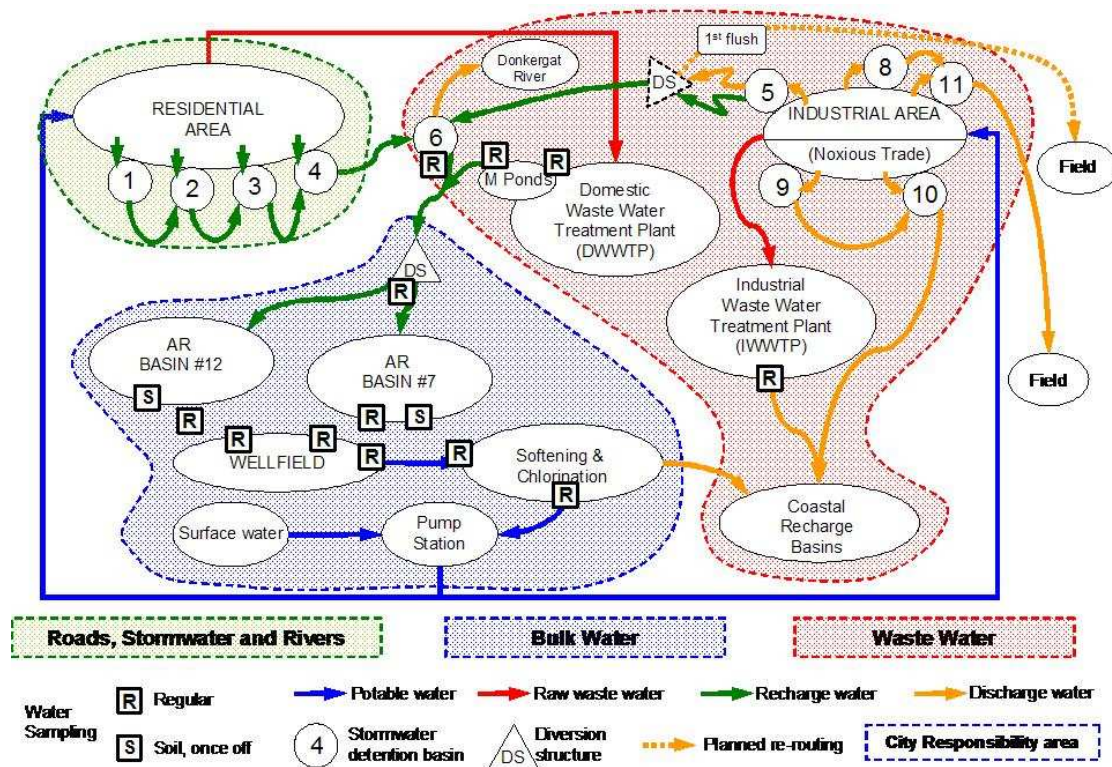


Figure 4: Plan of storm water detention and infiltration at the Atlantis Well Field, Western Cape

The participation of the CSIR in the EU Project “RECLAIM WATER” centres on the Atlantis water resource management scheme, which incorporates the reuse of wastewater and urban stormwater runoff shown in figure 4. Due to the aridity of the area, water supplies are limited and artificial recharge was introduced for augmenting local groundwater supplies. Artificial recharge of secondary treated domestic wastewater after 10 – 14 day retention in maturation ponds, together with urban stormwater runoff, has been practised for more than 25 years. The Atlantis scheme faces several water quality management challenges, ranging from the control of saline water encroachment to industrial pollution threats and biofouling of production boreholes. The relatively thin unsaturated zone limits the attenuation capacity of the soil-aquifer system during basin recharge. On average, approximately 7500 m³ of water is recharged per day up-gradient of the well field, while some 4000 m³/d higher salinity industrial wastewater is treated and discharged into basins down gradient of the well field close to the ocean without further use for recharge. Hydrochemical

monitoring of the various water sources and the ensuing adaptation of recharge practices for protecting the overall quality of the groundwater resource has benefited the system. However, no detailed study of microbial contaminants and organic compounds has been carried out and the fate of such contaminants is unknown. The risk that the potable water poses to immune-compromised individuals has not been established. These aspects are now being addressed within the framework of the EU project. This project has 20 participating institutions worldwide and studies eight operational systems, of which Atlantis is one. Each of the systems has its own train of treatment processes from rudimentary to highly sophisticated membrane technology. Participation provides a unique opportunity to gain access to the latest information regarding safe water recycling.

5 - Conclusions

Groundwater resources in South Africa supply an estimated 50% of rural communities and have the potential to support development with further use. However, the sustainable use of groundwater in arid areas, areas with high nitrate and areas where ecosystems also require aquifers will depend on the application of science and technology piloted by the CSIR.

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