Orange-Senqu River Basin

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Key Issues Related to Groundwater Management in the Orange-Senqu River Basin

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Executive summary

The Orange-Senqu River basin has an area of nearly one million square km and includes a wide range of geological, geomorphological and environmental features as it passes from the Orange River headwaters in the Lesotho Highlands in the east towards the Namib Desert and Atlantic Ocean in the west. Long term average rainfall over the basin ranges from as little as 200 mm in the arid lowlands in the west to over 1,000 mm in the Lesotho Highlands. There is considerable inter-annual variation in rainfall with periodic sets of drought years. Groundwater resources are threatened by demography, pollution, land use change and over-abstraction.

The geological and hydrogeological setting for the basin includes two areas containing sediments of Karoo age and an otherwise irregular distribution of many and varied rock types ranging from the Archean basement rocks to the Quaternary Kalahari Beds. The upper part of the Karoo sequence contains a significant water bearing rock sequence and the Transvaal dolomites are also an important aquifer. Other strata contain some groundwater and offer generally small yields to support rural needs and the mining industry. Sustainability of supply is an issue with ever increasing demand set against periodic drought climate cycles. Estimates of recharge are complicated by the low effective rainfall in the arid and semi-arid areas and by the inter-annual variability of rainfall in the more humid parts of the basin. Long term average values for recharge of just 1 mm/yr in the west to 100 mm/yr in the east are of the correct order.

Overall understanding of the aquifer systems is patchy. Some areas have been studied in detail with comprehensive validated numerical flow models while other areas do not yet have even a conceptual understanding of flow. Difficulties in estimating recharge confuse water balance estimates so that the overall capacity of aquifers is largely unknown.

Groundwater quality, pollution and groundwater protection are also issues in the Orange-Senqu River basin. Acid mine decant is a current problem in parts of Gauteng where water stored in the dolomites drains into former mine workings to emerge as a decant that is damaging to the aquatic environment. Elsewhere shallow groundwater systems are liable to pollution from poorly sited pit latrines and other foci of surface and near surface pollutants. Disperse pollution of groundwater from application of nutrients and pesticides by the agricultural and forestry industries are also prevalent.

Data scarcity hinders detailed evaluation of the groundwater systems to be managed. Programmes of exploratory investigation, drilling and geophysics, will greatly help understanding of the major and minor aquifers alike. However, the key to improved data and understanding is routine data gathering during drilling testing and monitoring supported by a user friendly and accessible data base. The database needs to be shared by all stakeholders regardless of international borders. The data gatherers and data users need to work to a common protocol and to a common and shared level of understanding so that a sensible dialogue can be maintained between them. This is essential if the basin's overall surface and groundwater resources are to be managed to develop an

optimum sustainable yield. Drought and flood are problems that need to be coped with and strategies to reduce demand in times of drought need to be prepared. Environmental protection from over use of water resources is a vital component of management. Transboundary aquifers are not perceived as a priority issue at the moment.

For all these issues there are technical solutions. Technical solutions cost money and the limiting factor is not 'can it be done' but 'can it be afforded'. Cost effectiveness is, therefore, vital. Technical solutions include improved data gathering and data management, enhanced monitoring networks, sharing of data and understanding, establishment of groundwater protection zones, protection of the environment from acid mine decants and many other do-able projects. Improved access to data will enable more sophisticated investigatory techniques to be applied leading towards numerical modelling supported by historical data. Investigation of recharge is a priority as without this knowledge sensible management of the groundwater resources is not feasible. The technical solutions are described on a regional basis and summarised within the respective geological groups.

The challenges that are to be faced over the sustainable management of the groundwater resources within the Orange-Senqu River basin are significant but none are insurmountable. The management issues fall into two groups: physical measurement and monitoring to support understanding of the groundwater flow systems, and the basin-wide governance and oversight of the resources within the basin.

1. Introduction

The Orange-Senqu River basin comprises a large part of South Africa, Botswana, Namibia and Lesotho. It includes the Orange and Vaal river basins and the Fish River in Namibia. Climate ranges from arid in the south west, where the long term average annual rainfall is only 200 mm, through semi-arid in the central part of the overall basin to a better endowed rainfall regime in the Lesotho Highlands to the east where in excess of 1000 mm per year is typical. Rainfall is strongly seasonal and erratic year on year within the arid and semi-arid areas of the basin. Annual potential evaporation, without exception, exceeds long term average rainfall.

Water supply for domestic, industrial and agricultural users is provided from conjunctive use of surface water storage, river off-takes and groundwater. Throughout the region, however, groundwater is critical to supply and in many rural communities it is often the only reliable source of safe water. A primary issue for the region is food security and the management of the water resources in order to lessen the impact of both drought and flood. Climate change is perceived also as an issue but is likely to impact as much in temperature increase than any significant change in rainfall distribution. However, storm activity is likely to increase with a corresponding adverse impact on infiltration to groundwater reserves.

Groundwater is under threat from a number of different directions:

- Demography is a major stress factor which reflects increasing demand from a finite and variably renewable resource.
- Pollution both at sub-catchment scale by mining, industry and intensive farming and at a local and community scale by point sources such as mine spoil heaps, waste facilities and even pit latrines is a major cause for concern.
- Land use change, particularly in marginal dry land areas, tends to work in favour of runoff at the expense of infiltration as vegetation is denuded.
- Competition for water between different user interests tends to encourage over-abstraction and groundwater ‘mining’. This is pertinent in the case of transboundary aquifers (TBAs) such as those between Namibia, Botswana and South Africa and between Lesotho and South Africa although none of these aquifers contain significant resources.

A gap analysis was carried out for the basin (ORASECOM, 2007) which concluded that the key technical needs were:

- The majority of the available groundwater resources are already utilised and improved data gathering and better technical understanding are critical to support management of these resources. There is some scope for new development, e.g. north of Middlepits in Botswana and possibly in the Lower Kalahari Beds.

- Groundwater recharge across the basin is poorly understood and needs to be a focus of investigation by application of groundwater balance studies.
- There should be better application of conjunctive use of groundwater and surface water.
- There is a need for hydrochemical and hydrocensus baseline studies along with expanded monitoring networks in many aquifers.
- A broader investigation the pollution hazard from pit latrines, mining and agriculture is required.
- There is a need for improved data management and sharing of data between mining companies and consultants with national governments.

Specific technical needs were given as:

- Obtain permeability and porosity data for main aquifers from borehole cores.
- Geophysical logging of boreholes to assist in aquifer characterisation.
- Investigation of the sustainability of existing wellfields.
- Numerical groundwater modelling developed as a strategic planning tool.

Considerable progress has been made in the last six years since this gap analysis was carried out. For example, technical investigation of recharge using tracers has been undertaken in the Northern Cape and elsewhere and groundwater modelling is now more widely deployed. However, borehole geophysical logging currently undertaken in a groundwater context within the basin remains minimal and crude salt tracer tests are often all that are used for borehole flow investigations; cored boreholes are expensive and rarely drilled so there is little opportunity for laboratory analysis of cores.

In general the specific technical issues identified during the gap analysis and that require attention can be summarised:

- Groundwater contamination by rural pit latrines in the upland areas of the basin where the aquifers tend to be shallow and vulnerable.
- Contamination from both agriculture and mining in the central basin are coupled with severe competition for resources.
- Unsustainable groundwater mining in the lowland areas of the basin in the arid and semi-arid environments.

The current paper identifies the key basin-wide groundwater issues and puts forward technical solutions that may be applied. It provides factual background information in support of the Strategic Action Programme and the respective National Action Plans for each basin state.

2. The Orange-Senqu River basin

2.1 Geo-environmental setting

The Orange-Senqu River basin has an area just less than one million square km and includes a very wide range of geological, geomorphological and environmental features as it passes from the Senqu River headwaters in the Lesotho Highlands in the east towards the Namib Desert and Atlantic Ocean in the west. In summary these are:

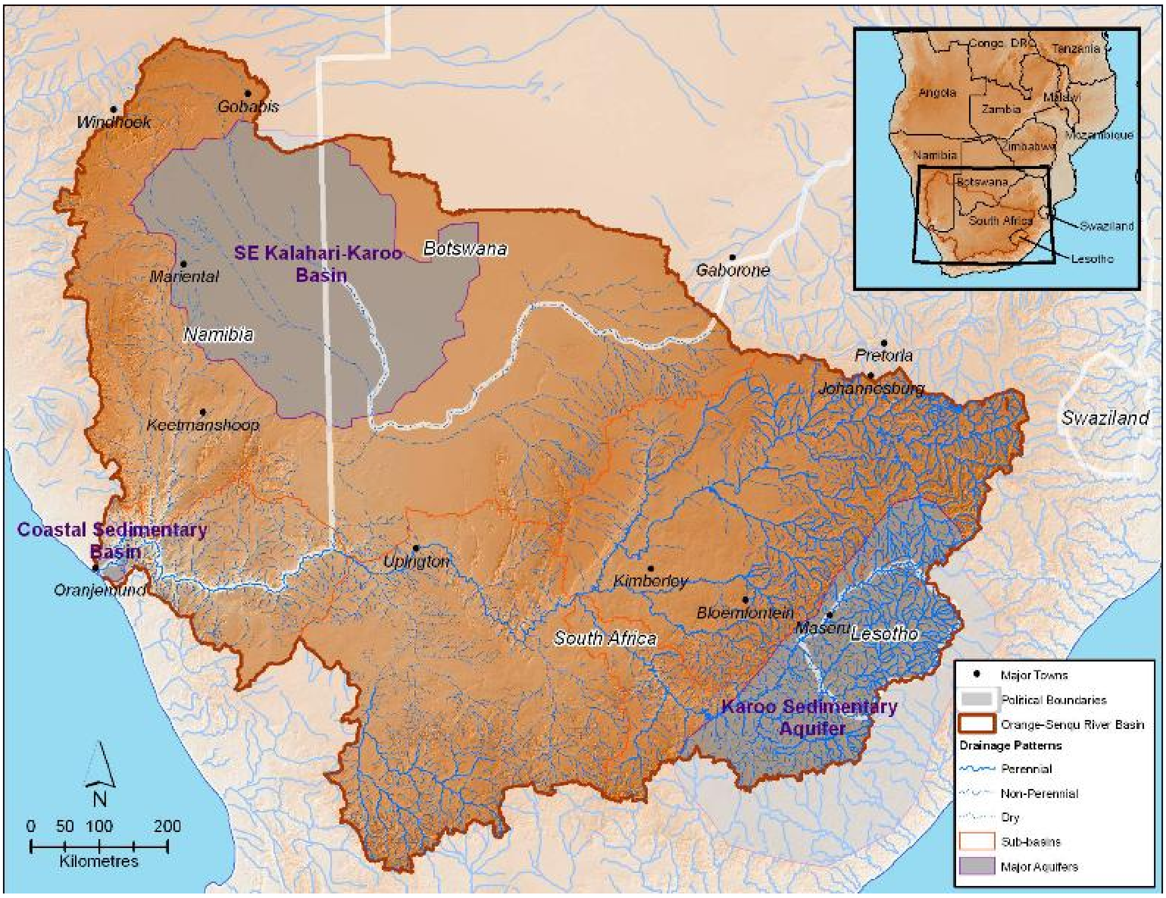
- Maluti Drakensberg Mountains
- South African Highveld
- Nama Karoo
- Southern Kalahari
- Namaqua Highlands
- Southern Namib desert.

Moving down the basin the steep sided valleys of Lesotho give way to the more mature landscape of the Highveld and in turn the rolling lands of the Nama Karoo and the grassland of the Kalahari. The Lesotho Highlands support alpine vegetation and shrubs, the Highveld and Karoo are characterised by grassland giving way to mixed sour grassland in valleys and lower elevation areas while the desert is characterised by grassland and small shrubs. Only 7% of the overall basin area is cultivated.

The geological setting of the region reflects prolonged sedimentation over ancient basement rocks, during which several periods of erosion left an incomplete succession and an irregular distribution of the many and varied rock types (see Johnson et al., 2006). In the highlands of Lesotho there are a variety of rock types including sandstones, dolomites, lavas and basalts belonging to two series of the Mesozoic Karoo system. The upper layer consists of basalt lavas up to 1,500 m thick, underlain by Cave Sandstone, Molteno Beds and the Upper Beaufort Beds. The Karoo sediments continue westwards into the main Karoo basin around Gauteng, NW Province and Northern Cape Province. Another large Karoo sedimentary basin is centred on the Botswana and Namibia Kalahari regions, although concealed by Quaternary Kalahari Beds. The Orange River traverses many ancient geological units with some of the oldest rocks exposed in the Orange River valley near its confluence with the Fish River in Namibia (Figure 1).

Climate is dominated by a distinct rainy season between November and April as the Inter-Tropical Convergence Zone moves south, and dry winters in June to September. However, rainfall in the arid lands in the western portion of the basin is irregular and parts of the Fish River catchment may not receive rain at all during many summers. Elsewhere the summers are characterised by hot and humid weather with rainfall mostly occurring as storm events. The east to west decline in long term average rainfall across the basin reflects the effects in the continental interior of the warm currents of the Indian Ocean which generate moisture and the cold Benguela Current of the Atlantic Ocean which generates dry air.

Figure 1: The Karoo basins in the Orange-Senqu River basin



Aquifers

The principal sub-catchment scale aquifers in the Orange-Senqu River basin largely comprise the granular sedimentary strata within the Karoo sequence, the partly karstic dolomites belonging to the Transvaal Supergroup and the fractured arkosic metasediments of the Waterberg Supergroup (see SADC Hydrogeology Map *http://www.sadcwaterhub.org/content/explanatory-brochure-southern-african-development-community-sadc-hydrogeological-map-atlas*). Groundwater movement within all these aquifers is heavily dependent on fractures and karst solution features while groundwater storage is mainly intergranular in the Karoo sedimentary deposits but less so in the dolomite and metasedimentary rocks. Classic porous media aquifers are limited to parts of the Quaternary Kalahari Beds and recent fluvial deposits along the major river valleys. Elsewhere the 'hard' rocks of the Achaean and Proterozoic basement allow some groundwater storage and transport within a shallow weathered zone called the regolith, which comprises a granular zone overlying fractured rock, the base of which is usually not more than 40 m below ground level. However, on the older continental erosion surfaces weathering may continue past a granular phase towards clay which then inhibits infiltration of rainwater and recharge to the regolith aquifer.

The two major Karoo sedimentary basins are situated within the south eastern and central part of the Orange-Senqu River basin and in the north western Kalahari zone. The Karoo Supergroup is divided between the Dwyka and Ecca Groups at its base to the youngest volcanic Drakensberg and Lebombo Groups at the top. It is the latter that form the high ground of Lesotho, while the oldest rocks of the Dwyka and Ecca form a ring through Kimberley towards southern Gauteng and east towards Swaziland. The intervening component groups of the Karoo young westwards from Lesotho towards this ring of older sediments. Although groundwater occurs throughout much of the sequence, the granular Middle and Upper Karoo formations within the overall sedimentary pile offer the most favourable conditions for groundwater storage and therefore the greatest groundwater supply potential. Members of the Karoo Supergroup also underlie the Kalahari basin and thus underlie much of the Kalahari Beds outcrop in Botswana and Namibia. Again, many of the granular strata are water bearing although in this basin groundwater may not be actively recharged, groundwater gradients are extremely low, and many aquifers are brackish or saline.

The Proterozoic Transvaal dolomites underlie a broad band between Johannesburg and Pretoria, westwards towards Mafikeng. Groundwater circulation takes up the calcium and magnesium bicarbonate minerals in solution to create enlarged fractures, caves and passages along which the legendary 'underground rivers' may flow. Groundwater occurrence is specifically contained within these features and is not easy to exploit unless a borehole penetrates one or more water bearing fracture or karst features. Similarly, groundwater in the Waterberg metasediments is contained in fractures with minimal intergranular permeability.

The Kalahari Beds have the potential to be a productive aquifer where they are in receipt of recharge, usually secondary recharge from ephemeral rivers and streams. However, in the main there is little groundwater to be had in these deposits although pockets of productive Kalahari Beds do occur both in Botswana and Namibia, particularly where the lowermost gravely units are below the regional piezometric surface.

Alluvial valley fill material in contact with surface river water is a productive primary aquifer that is used throughout the basin for irrigation supply water and other intensive water uses. It is not evenly distributed and is not a major aquifer in the regional scale of the Orange-Senqu River basin.

Recharge and groundwater flow systems

Potential recharge is that part of rainfall that is not returned to the air as evaporation or transpiration minus that part which runs off to streams and rivers. Throughout much of the basin, however, evaporation exceeds rainfall so that potential recharge can only possibly occur during prolonged storm events.

Actual recharge to groundwater comprises the downward flow of potential recharge that percolates through the upper unsaturated part of the aquifer to reach the water table. It may occur from both rain falling on the ground and from secondary recharge caused by percolation of runoff and standing surface water. Recharge is the single most important value for determining the long term capacity of an aquifer and underpins the sensible management of the resource. It is a notoriously difficult parameter to determine although a range of different techniques can be applied to estimate regional and point values of recharge. While accurate measurements can be made at point scale using lysimeters and moisture profiling methods, these are both expensive to operate and difficult to upscale. Water balance calculations are the most commonly applied method for determining recharge while chemical methods such as chloride mass balance using the difference in chloride concentrations in rainfall and groundwater are nowadays supplemented by a variety of tracer techniques. Radioactive isotope techniques have also been widely applied in the Kalahari areas where inherent high salinity and dubious meteorological data may preclude other methods.

Reported values for recharge throughout the Orange-Senqu River Basin vary by a factor of 100 for measurements within areas of roughly equal long term average rainfall. The most consistent data derive from water balance calculations and models, whereas chloride mass balance calculations tend to overestimate and baseflow separation techniques underestimate the value (Xu & Beekman, 2003). Long term average values of rainfall for the Basin range from just 1 mm/yr in arid areas with a rainfall expectation of <500 mm/year, up to 100 mm/yr where rainfall attains up to 1,000 mm/yr and two or three times this value where rainfall attains 1500 mm/yr. However, these are long term averages and the actual yearly value in any of these three rainfall zones may range from virtually zero during drought climate cycles to significantly higher values in summers characterised by prolonged intensive storm activity. Typical long term average recharge values for the Highveld, therefore, range between 25 and 100 mm/yr.

Once recharge has arrived at the water table it is free to move laterally down the prevailing hydraulic gradient to discharge eventually as spring flow to surface and baseflow to rivers. Interception from the flow regime by abstracting boreholes impacts spring and base flow discharges. In the karst dolomite aquifer the gradient of each karst feature dictates the flow direction so that flow occurs through a discrete network of inter-connecting fissures. In the fracture aquifers of the Karoo the flow follows the secondary porosity provided by the fractures while most of the storage is contained within the porous rock media. The flow direction is essentially driven by surface topography with groundwater flowing from beneath the interfluves towards the valleys on a catchment scale and down the length of the major river basins. In the axial zones of the deeper Karoo basins hydraulic gradients may be virtually non-existent and the groundwater is essentially ‘stagnant’ leading to increased salinity, and almost no groundwater ‘emergence points’ exist. That being so, none of the individual aquifers in the Orange-Senqu River basin are large enough to effect overall basin scale flow, while the lesser basement rock aquifers only allow local scale flow towards abstraction points and lower elevation land.

Groundwater potential capacities

Given the nature of the aquifers in the Orange-Senqu River basin, the range in long term average recharge and the difficulties in calculating it and the different scales of the various types of groundwater flow systems, it is not surprising that overall groundwater potential capacities for these aquifers are poorly understood. This lack of understanding is dangerous given that groundwater use in the basin is relatively large with respect to industrial and agricultural production and crucially important with respect to human consumption since a substantial proportion of the people living in the basin, other than those living in main urban centres such as Johannesburg and Pretoria which are supplied from surface dams and the Lesotho Highlands Water Transfer Scheme, are dependent on groundwater for their drinking water supply.

Surrogate groundwater capacity maps have been produced for part of the basin, for instance the groundwater harvest map by Department of Water Affairs, South Africa (1: 3,000,000 scale, see *http://www.dwaf.gov.za/Geohydrology/Maps/harvpot.asp*) combines a number of measurable properties from boreholes to an index of productivity. At worst, groundwater availability maps have been produced which mirror groundwater dependence and groundwater availability. In general, formation constants such as permeability (the ability of the aquifer to transport groundwater) and storativity (the amount of water stored per unit volume of the aquifer) are not available and surrogate values such as specific capacity (the yield of a borehole divided by the amount the pump draws down the water level over a set period - commonly 3 hours) need to be applied to the analysis of aquifer flow and storage. These data are essential for developing numerical groundwater flow models that can test conceptual groundwater flow visions. Numerical models are essential for running 'what if' scenarios' such as increased abstraction from a wellfield or change in prevailing rainfall and evaporation.

Thus, in determining groundwater potential capacities for whole aquifers or part aquifer units, a whole raft of issues emerge. These are:

1. *Aquifer units in the basin are of sub-catchment scale and are largely fracture flow dominated or karst with the exception of local valley fill material and the Kalahari Beds. Analysis of groundwater flow characteristics in fractured aquifers is complicated by various assumptions that need to be accepted but which imply uncertainty on the results. For example, Darcian flow and the many equations that depend on it assumes a porous, homogeneous and isotropic medium; none of the aquifers in the Orange-Senqu River basin fit this criterion.*

2. *Determination of recharge is difficult in arid and semi-arid climates because rainfall is intermittent and on a long term average basis evaporation greatly exceeds rainfall. Values range by a factor of 100 in the Orange-Senqu River basin for comparable rainfall magnitudes.*

3. *Actual volumes of groundwater in store in the aquifers are not readily calculable. The variable nature of the Karoo aquifers and the dolomites and metasediments as well as the presence of hydraulic barriers such as dolerite dykes inhibit accurate calculation of storage.*

4. *Valley fill and alluvial aquifers draw heavily from the interaction between the groundwater stored in the aquifer and water in store in the adjacent stream or river. This interaction is difficult to quantify and requires collaboration between hydrological monitoring data and groundwater data.*

5. *Lack of formation constant data seriously inhibits groundwater modelling exercises with which to test the perceived groundwater flow system and analyse the effects of climate change or increased demand on the resource.*

The technical solutions to these issues are complex and expensive and a balance needs to be made between 'essential to know' and 'nice to know'. The issues become more critical from east to west across the basin, i.e. from wetter to dryer climates. Conventional hydrogeological analysis is required to determine conceptual groundwater flow models and to develop water budgets with realistic estimates of recharge and groundwater throughflow. Such work needs to be carried out on a local basis and expanded to sub-catchment and subsequently catchment scale to allow an overall understanding of how each aquifer works and what level of abstraction it can sustain. The approach would be to first study the 'hotspots', areas of intense abstraction for agriculture, mining and industry, with the goal of creating enough understanding to develop realistic numerical groundwater flow models which will allow predictive 'what if' scenarios to be run. The two main aquifers for such focussed study are undoubtedly the Transvaal dolomites, important because they support the most dense concentration of people and activities, and the Karoo sediments, equally important to sustain agriculture, mining and people.

The solution needs to commence by creating a comprehensive catalogue of the groundwater studies already carried out within the Basin. Much of the work is reported as 'grey data' and is held privately by consultants and mining houses so this is no easy task. Given this initial catalogue a gap analysis will then reveal the priority knowledge shortfalls that would require to be filled in order to underpin management of the groundwater resources for sustainable use. This is a major task but is a task that the river basin managers need to encompass and oversee in collaboration with the respective national regulators.

Groundwater quality, pollution and protection

A serious issue in parts of the Orange-Senqu River basin is that of groundwater pollution. For example, the pollution currently derived from acid main drainage decants in the dolomites in the Gauteng region of South Africa is cause for great concern. In the Krugersdorp area alone, former gold mining activity discharges an acid, metal rich decant to surface waters with serious consequences to the aquatic environment. The underlying aquifers are similarly contaminated so that the groundwater cannot be used sensibly for agricultural or industrial purposes. In Gauteng, mine spoil heaps continue to leach metal rich decant into the dolomite aquifer contaminating significant areas of the aquifer, although by comparison in the more arid mining areas of Botswana, leachate generation is less of a problem and easier to contain.

Contamination may also occur from a number of everyday point and linear sources. Fuel stations, although protected by double lined tanks, can leak, and chemical stores, spillages on roads and railways, can all contribute to an ever increasing load of organic and inorganic compounds that may eventually reach the water table. At a more dispersed level intense agricultural activity, such as nitrate application to grassland, pesticides, for example on Orange trees, release of nutrients from tree felling and so on, all pose a threat to groundwater quality.

At a local community level, waste disposal and pit latrines may contaminate local wells and boreholes and care is needed to ensure that *faecal coli* and other hazards are not returned to the water supply. Particular care is needed on the dolomite aquifer where the pathway between source and receptor may be rapid. This was illustrated by an outbreak of typhoid in the town of Delmas in Mpumalanga in September 2005, despite chlorination of the supply. The problem was traced to informal settlements on the dolomite from which faecal coli were transported to the aquifer.

The key issues are:

6. Pollution of groundwater can occur from a variety of sources. It is generally not visible and needs to be monitored both for quality and distribution. This can be expensive and the 'polluter pays' principle may not easily be applied.

7. Pollution already adversely impacts large areas of many of the main aquifers in the Orange-Senqu River basin and it brings with it a considerable cost to potential groundwater users.

8. Contamination of individual water sources at rural village level is a separate problem and relates largely to inadequacy of local protection zone measures.

9. Groundwater protection strategies and policies are generally not effective throughout the basin.

Technical solutions are many and varied depending on the type of pollution to be addressed. A major visible form of pollution is mine and mine waste decants which are a major problem in the dolomites in Gauteng and in parts of the Karoo. Detailed understanding of the source of the water supplying the mine overflow is needed, which thus focuses on recharge from surface waters as well as from direct rainfall recharge. Such understanding will allow insight into the possibility of intercepting good quality inflow water before it reaches mine voids so depleting the generation of mine decant and allowing supply of fresh water for use elsewhere. Various engineering solutions such as the capping of mine waste dumps to encourage rainfall runoff should also be applied more widely.

Dispersed agricultural pollution caused by excess application of nutrients and pesticides is a problem over both the Karoo and the dolomite aquifers. It is best tackled by regulating farming practice and outreach to farmers to explain the need for sensible application of chemicals to their crops.

Urban and rural community pollution is a serious problem from the uplands of Lesotho right down the basin to the dry flatlands of Botswana, Namibia and the Northern Cape. This has to be tackled primarily by education but also by proper management of potential pollution sources at local level. However, such management needs to be to a uniform standard and needs oversight.

Data scarcity and data needs

Just as permeability and storativity values are not generally available for the various groundwater systems in the Orange-Senqu River basin, so other data essential to support groundwater management may also be lacking. Borehole completion data including well design, depth, geological logs, test pumping data, groundwater chemistry are available for some wellfields and some major sources, but for the most part these data are incomplete. The most valuable data, the occurrence of dry boreholes or wells, are almost never recorded, resulting in a positive skew to all statistical analyses and encouraging significant and often wasted expenditure on groundwater exploration and development where previous unrecorded experience has demonstrated no groundwater is to be had.

Data needs correspond to the required level of understanding of an aquifer system. Meteorological data and hydrological streamflow data are generally available, in broad terms, from local observations and models. Groundwater level hydrographs, essential for verifying recharge calculations, are available at selected locations but data are inadequate for an overall evaluation of each aquifer unit in the basin. In addition, understanding the aquifer response to drought periods in which a succession of summer rains fail is fraught with problems because the required long term groundwater monitoring tends to suffer at the expense of 'fire-fighting' the effects of the drought. As a consequence, the effect of drought on groundwater systems in the basin remains poorly understood.

The key issue remains:

10. Essential data on aquifer systems, specifically borehole derived data, are scarce throughout the region. Basic valuable data may not be recorded including dry boreholes and wells, and the opportunity to measure and record during the drilling and commissioning phase is often overlooked.

There is no immediate technical solution to this problem. The solution lies in the deployment of sufficient technical staff and resources with the objective of collecting physical and chemical data to a set and agreed protocol with which to support conceptual groundwater flow models and water budgets. Groundwater modelling is always a useful exercise at it reveals gaps in data which may then be addressed before a properly validated model can be achieved. The essential solution to data gathering is vision and resourcing.

2.2 The stakeholders and water users

Governmental through to ecological

The Orange-Senqu River basin straddles four countries and groundwater regulation and management is controlled separately by those four states. Governmental capacity and aspirations are different in each state and national average per capita earnings vary considerably. This diversity of government means that no single set of regulatory obligations exist across the whole river basin; this in itself is not a problem as the regulations are designed to suit the needs of both the state they apply to and the environmental, social and economic conditions prevailing in each state. It becomes a little more complex when it is realised that each state applies a different model of water governance: South Africa, for example empowers the municipality with responsibility to distribute water, whereas Botswana and Namibia vest this responsibility with parastatal Water Utilities Corporation and NamWater respectively. Groundwater, being out of sight, tends to remain poorly regulated with a lack of abstraction and water level monitoring once the initial licence is granted. This means that abstraction data are scarce and those that do exist are based on generic information rather than measured data.

Considerable effort has been made by governments to address drought and flood. Nevertheless the realisation that drought is a regular occurrence and more effort is being made to 'drought proof' communities and their wellbeing. Nevertheless the periodic onset of more acute drought conditions continues to generate an emergency, rather than a measured response, despite the memory of the severe drought of the early 1990s and the cost of dealing with lessening its impact. At that time many new boreholes were drilled as a short-term supply measure with little regard for sustainability and many of these boreholes fell into disuse as the supply later failed. Other emergency measures used in the Orange-Senqu River basin included tankering, a desperate means of maintaining basic supplies that is both expensive and unsustainable.

In the past decade attention has begun to be given to environmental legislation, including minimum spring flow discharges from groundwater to maintain ecologically significant environments. Greater attention to groundwater and surface water interaction, both in the riparian zone and at wetland areas, will be required in future.

Key issue is:

11. Governance of the Orange-Senqu River basin is divided four ways between each of four countries. Although there are hopes of a uniform approach to managing the groundwater resources of the basin by the basin commission these are yet to be realised. Some aspects of groundwater management such as protection of the surface environment are not effectively carried out.

The technical solution to help address this issue is adoption of a uniform approach in each basin state to data gathering, analysis and reporting. This can be achieved by networking through regular collaborative workshops to discuss understanding of aquifer units common to more than one country in the basin. Commonality already exists in the form of the science of hydrogeology and hydrogeological training. However, there is no single route to obtain detailed understanding of an aquifer system and a full dialogue between investigators and stakeholders is essential.

Demand - the groundwater users - future demand

Estimating current overall demand for groundwater throughout the basin depends largely on statistical information, while calculations of future demand may depend on a range of variables each with its own uncertainties. Groundwater abstraction monitoring is carried out at only a few select sites, notably at the mines in the semi-arid and arid lands that depend on water for production, the public supply wellfields in Namibia and Botswana, and other large user centres throughout South Africa. This paucity of data does not contribute usefully to water balance calculations and adds another degree of uncertainty to the sustainable management of the resources.

Demand is to a large extent dictated by availability and cost. Shallow groundwater resources in the weathered basement rock aquifer can be accessed with hand dug wells and boreholes that can be installed cheaply and groundwater, albeit generally only modest yields of between 0.5 and 2 l/s, can be raised by hand pumps. Deeper resources such as the Karoo aquifers beneath the Kalahari Beds in Namibia and Botswana are more expensive to access, requiring deeper boreholes and motorised pumps. As a consequence dry land ranching in Botswana and Namibia is inhibited by the cost of installing deep boreholes into the Karoo while shallower resources in South Africa allow less costly access to the groundwater for agricultural and other purposes

The key issue is:

12. Scarcity of groundwater abstraction monitoring data adds another uncertainty to water balance calculations and hinders the sustainable management of the resource. Groundwater demand projections are, therefore, difficult to forecast.

The technical solution is a uniform approach to groundwater monitoring across the basin which focuses on the 'hotspots' but which also gathers data within a spatial network that will allow complete understanding of the reaction of the aquifer to drought and flood climate cycles, demography and increased pressure on the aquifer, and changes in water quality. Existing networks in South Africa, Botswana and Namibia largely provide information on major wellfields although there is some more dispersed baseline data being collected as well. There is, however, a significant requirement for many more observation boreholes isolated from pumping which will better reflect the natural status of the aquifer and specifically the response to climatic change.

Management networks

Management of the groundwater resources within the Orange-Senqu River basin ultimately requires a comprehensive management network within the Basin Commission working towards a common goal within an agreed protocol. Discussion between basin states is a valuable start to such collaboration, but a greater degree of interstate collaboration through data sharing, monitoring and analysis will provide a better understanding of the overall resource potential. This will require adjustment of governance models and in strategy and policy within each of the four countries within the basin. Precedence for such collaboration can be illustrated in South America where a working collaborative governance model for the major transboundary Guarani Aquifer shared by Argentina, Brazil, Uruguay and Paraguay has been developed. In the southern Africa region SADC has made considerable progress in developing collaborative interstate networks covering a variety of fields although groundwater governance is not yet one of them.

The issue is:

13. Reluctance of national authorities to comply with international needs in order to better manage available resources.

Supply and demand – sustainable resources

The management vision for any aquifer system is the sustainability of the resource in both quantity and quality. It is feasible to mine groundwater in order to satisfy a current need over a specific time period, and this is likely to be the basis of the groundwater supplies to the larger mines in the semi-arid and arid lands in the west of the Basin. Groundwater mining is acceptable only if the project is finite and that a subsequent recovery period is provided before abstraction can begin again or an alternative supply can be brought on stream. Examples are the extensive mine dewatering programme carried out at the Kimberley mine until work ceased in 1914, where subsequent groundwater level recovery has only achieved a water level rise of 40 m rather than the 100 m needed for full recovery, and the Hotazel manganese mine in the Northern Cape (in South Africa) where the current dewatering programme is having a negative effect on groundwater levels in the vicinity. However, mining activity in the Kalahari at both Orapa and Jwaneng (both in Botswana) is not currently perceived to be mining groundwater to permanent depletion and groundwater abstraction and mine dewatering are believed to be at sustainable rates, despite Jwaneng now working at depths approaching 400 m below ground.

Sustainability of supply vies with economics to optimise the resource potential and to ensure equitable allocation between stakeholders and all types of water users. For example, rural community needs may compete with those of the local mining company and care is needed to ensure both parties are satisfied. In addition, the complexities of managing both wet climate cycle years and drought years using drought mitigation strategies to moderate the impact of drought need to be encompassed in the management strategy. Clearly, in order to establish the optimum level of use, data need to be available with which to analyse both the water balance and the groundwater flow system. For the most part these data are usually inadequate and both monitoring and data gathering need to be substantially enhanced.

One of the better examples of technical understanding of the groundwater resource potential and its optimum use conjunctively with treated and recycled waste water is that of the Windhoek urban supply. Here wellfields draw groundwater at a rate understood to be sustainable and this is blended with recycled water to make up the shortfall in supply.

Interestingly the unit cost of the treated recycled waste water is less than that of the groundwater pumped to surface, treated and then pumped to the storage works ready for blending and supply.

The key issues and need for resolution is:

14. Lack of understanding of the optimum resource potential of the aquifers throughout the Orange-Senqu River basin.

15. Drought management and coping strategies.

As noted earlier, the technical solution to these issues is better understanding of how aquifers in the basin work. Again this is dependent on staffing and resources and is best rolled out from the 'hotspots' to areas that are not under significant stress.

2.3 Transboundary aquifers in the basin

A transboundary aquifer (TBA) is a groundwater unit shared by two or more nations. Cross-border impacts need to be assessed in order to establish if international co-operation and management of the aquifer system would help towards equitable allocation of the shared resource. The difficulties of conceptualising flow in a TBA are exacerbated in the semi-arid and arid regions where hydrogeological data are sparse. Cross-border aquifer management may be unwarranted if demand is low on both sides of the border, where land is sparsely populated.

TBAs can be classified as having the potential to be the cause of tension between neighbouring states, i.e. politically sensitive or politically troublesome, and those unlikely to become problematic even in the future, i.e. in no particularly urgent need of shared management. The stakeholders need to be armed with this classification to know which TBAs are likely to be troublesome and, therefore, in need of management and those which are not currently in need of management intervention (See Appendix 1).

Key issues are:

16. *TBAs are a political issue and standardised data collection, comparison and harmonisation across borders are proving to be a key challenge.*

17. *There is a clear need for some collaborative monitoring and analysis between neighbour states.*

The technical solution is better understanding of the transboundary aquifers. This is not currently seen as a priority issue for the Orange-Senqu River basin.

3. Solution of key issues

The solutions to virtually all issues raised in this paper are both technical and managerial and the two are interlinked. A cross-cutting constraint to both the technical and managerial issues is essentially the availability of adequate staffing and resources coupled with education. This solution can only be tackled at national level by recognising the importance of groundwater to the nation and applying the right level of financial resources to education, staff development and support systems. Such investment in human capital can also be supported regionally within the SADC framework, for instance by the establishment of the proposed Groundwater Management Institute of Southern Africa.

Technical solution responses fall between essential 'need to know' in order to understand the aquifer adequately to inform its sensible management and 'nice to know' in support of the broader understanding of the aquifer system. Essential technical understanding is developed through a set procedure regardless of the scale of the investigation:

- Preliminary investigation and data gathering and monitoring to develop an initial baseline and then a time series listings of groundwater levels and quality.
- Conceptual understanding of the groundwater flow system and the water budget built upon knowledge of aquifer characteristics, recharge etc.
- Development of representative numerical groundwater models to test 'what if' scenarios over time and space.

The solutions to the specific issues that have been identified are detailed in Table 1 in an overview format and specific to individual groundwater units in Table 2.

Table 1 Issues and technical solutions within the overall basin

	Issue	***Action required***	***Possible focus areas***
1.	Aquifer units in the basin are of sub-catchment scale and are fracture flow dominated or karst with the exception of local valley fill material and the Kalahari Beds. Analysis of groundwater flow characteristics in fractured aquifers is complicated by various assumptions that need to be accepted but which imply uncertainty on the results. For example, Darcian flow and the many equations that depend on it assumes a porous, homogeneous and isotropic medium; none of the aquifers in the Orange-Senqu basin fit this criterion.	Detailed regional hydrogeological studies are required to better understand the complex aquifer and groundwater systems that prevail in the region.	Transvaal dolomite aquifer (South Africa)
2.	Determination of recharge is difficult in arid and semi-arid climates because rainfall is intermittent and on a long term average basis evaporation greatly exceeds rainfall. Values range by a factor of 100 in the Orange-Senqu River basin for comparable rainfall magnitudes.	Greater effort is required to evaluate recharge potential within the various overall rainfall regimes and aquifer types. This needs to be carried out with regard also to climate change scenarios.	Upper Karoo aquifers (Lesotho)
3.	Actual volumes of groundwater in store in the aquifers are not readily calculable. The variable nature of the Karoo aquifers and the dolomites and the presence of hydraulic barriers such as dolerite dykes inhibit accurate calculation of storage.	Detailed assessment of groundwater storage in each aquifer unit needs to be made. This will require drilling and geophysics to support data gathering for the assessment.	Middle Karoo aquifers (South Africa)
4.	Valley fill and alluvial aquifers draw heavily from the interaction between the groundwater in store in the aquifer and water in store in the adjacent stream or river. This interaction is difficult to quantify and requires collaboration between hydrological monitoring data and groundwater data.	Focus of effort on groundwater and surface water interaction to assess the relationship between valley fill deposits and stream low flows.	Upper and Middle Karoo aquifers with Kalahari cover (Botswana, Namibia, South Africa)
5.	Lack of formation constant data inhibits groundwater modelling exercises with which to test the flow perceived groundwater flow system and analyse the effects of climate change or increased demand on the resource.	Concentrated effort is necessary to measure and collate basic hydrogeological parameters with which to evaluate groundwater resource capacities.	Basin-wide study of recharge over the principal aquifer units on west to east axis.

	Issue	***Action required***	***Possible focus areas***
6.	Pollution of groundwater can occur from a variety of sources. It is generally not visible and needs to be monitored both for quality and distribution. This can be expensive and the 'polluter pays' principle may not easily be applied. Pollution does sterilize large areas of the main aquifers in the Orange-Senqu River basin and it comes with a considerable cost to potential groundwater users. Contamination at rural village level is a separate problem.	Application of Pollution Vulnerability Mapping at basin scale; delineation of pollution, polluters and aquifer impacts.	Transvaal dolomite aquifer (South Africa)
7.	Groundwater protection strategies and policies are not effective throughout the basin.	Identification of rural village level 'hotspots	Upper Karoo aquifers (Lesotho)
8.	Essential data on aquifer systems, specifically borehole derived data, are scare throughout the region. Basic valuable data may not be recorded including dry boreholes and wells, and the opportunity to measure and record during the drilling and commissioning phase is often overlooked.	A review of the legislative controls on pollution. Move towards a uniform basin-wide pollution management system. Development of policies and strategies to tighten governmental control over pollution and clean-up activities.	Middle Karoo aquifers (South Africa)
9.	Governance of the Orange-Senqu River basin is divided four ways between each of four counties. Although there are hopes of a uniform approach to managing the groundwater resources of the overall basin by the basin Commission these are yet to be realised. Some aspects of groundwater management such as protection of the surface environment are not effectively carried out.	Focus on collecting drilling and new borehole commissioning data, archiving and data access.	Upper and Middle Karoo aquifers with Kalahari cover (Botswana, Namibia, South Africa)
10.	Scarcity of groundwater abstraction monitoring data adds another uncertainty to water balance calculations and hinders the sustainable management of the resource. Groundwater demand projections are, therefore, difficult to forecast.	Move towards uniform groundwater data collection, archiving, management and overall governance throughout the basin.	Basin-wide study to identify and quantify alluvial aquifers in the Orange and principal tributaries. Pilot area investigations in different surface water/climatic regimes.
11.	Reluctance of national authorities to comply with international needs in order to better manage available resources.	Focus on gathering groundwater hydrograph data and other time series information such as water quality.	Basin-wide groundwater archiving system; collection and collation/QA of maximum existing data from all sources. Data assessment and outputs.

	Issue	*Action required*	*Possible focus areas*
12.	Lack of understanding of the optimum resource potential of the aquifers throughout the Orange-Senqu River basin.	Promote dialogue between basin state governments and between other stakeholders within the basin.	Basin-wide pollution vulnerability mapping study.
13.	Drought management and coping strategies.	Improve monitoring networks and date gathering protocols.	Detailed studies in urban/industrial, agricultural and rural zones over principal aquifers.
14.	Standardised data collection, comparison and harmonisation across borders are proving to be a key challenge.	Given a better understanding of the groundwater flow regimes, a better drought management strategy can be developed to lesson impact of dry climate cycle periods.	Basin-wide review and policy development
15.	The TBAs are a political issue.	Dialogue towards standardisation	Transvaal dolomite aquifer (South Africa)
16.	Need for collaborative monitoring and analysis between neighbour states.	In reality they are of such limited capacity that they are not significant management issues for the Orange-Senqu River basin as a whole.	Upper Karoo aquifers (Lesotho)

Table 2 Issues and technical solutions for each aquifer unit occurring within the basin

Aquifer unit			***Overall lithology***	***Management issues***	***Technical solutions***
Subgroup/ formation	***Group***	***Supergroup/ complex***			
	Quaternary		Fluvial sediments	Vulnerable to surface and near surface pollution	Groundwater protection zones
	Kalahari		Unconsolidated to consolidated calcretes, sandstones, gravels, red clays and basal gravels	Groundwater quality	Protect fresh groundwater reserves from brines and brackish water within the aquifer sequence
	Drakensberg	Karoo Igneous Province	Extrusive basalts with extensive dolerite dykes and sills	Fractures and dyke contact zones vulnerable to pollution	Groundwater protection zonation
Clarens Formation		Karoo Supergroup	Dune bedded Aeolian sandstones; baked contact with overlying basalts; intruded by dolerite dykes	Competition for resources in aquifer divided by dykes; spring zones along baked contact with overlying basalts	Water balance studies for optimum sustainable development
Eliot Formation			Interbedded fluvial sandstones and mudstones; intruded by dolerite dykes	Sustainability	Exploratory investigations to determine long term yield
Molteno Formation			Fluvial sandstones; intruded by dolerite dykes	Competition for resources in aquifer divided by dykes	Water balance studies for optimum sustainable development
Tarkastad Subgroup	Beaufort		Fluvial sandstones subordinate mudstones; intruded by dolerite ring dykes in southern areas	Sustainability	Exploratory investigations
Adelaide Subgroup			Fluvial mudstones and thin sandstones	Sustainability	Exploratory investigations

	Aquifer unit		*Overall lithology*	*Management issues*	*Technical solutions*
Subgroup/ formation	*Group*	*Supergroup/ complex*			
	Ecca		Tillites, cyclic sediments with coal seams, feldspathic sandstones, basal carbonaceous mudstones	Sandstones for primary aquifers	Groundwater exploration, well design, high yields
	Dwyka		Diamictites, tillites, sandstones, mudstones and conglomerates	Poor groundwater prospects	Low yields
Kubbos-Bremen Suite			Granite	Low groundwater potential in shallow weathered and fractures horizons	Allow only small scale groundwater dependency
	Vanrhyns-dorp		Shallow marine cyclic grits, sandstones and shales	Low groundwater potential in shallow weathered and fractures horizons Drought susceptible	Allow only small scale groundwater dependency
	Nama		Shallow marine cyclic sandstones and shales and limestones	Low groundwater potential in shallow weathered and fractures horizons Drought susceptible	Allow only small scale groundwater dependency
		Gariep Supergp	Metavolcanic-sedimentary rocks with mafic intrusions	Low groundwater potential in shallow weathered and fractures horizons; Low yields vulnerable to pollution	Protect small scale rural supplies from pollutant sources
		Namaqua Metamorphic Province	Granitic gneisses, amphibolites and granitoids; various lead, zinc,copper and silver deposits	Low groundwater potential in shallow weathered and fractures horizons. Mine decant issues.	Conceptual flow modelling and numerical modelling
		Olifantshoek	Fluvial quartzites with some basalts towards base. Iron and manganese deposits at Sishen	Manganese and iron mines.	Conceptual and numerical modelling

Aquifer unit			***Overall lithology***	***Management issues***	***Technical solutions***
Subgroup/ formation	***Group***	***Supergroup/ complex***			
	Pretoria	Transvaal	Interbedded marine and deltaic sandstones and shales with some basaltic lavas	Low to medium groundwater potential in shallow weathered and fractures horizons. Manganese and iron mines – dewatering problems	Conceptual and numerical modelling
	Chunie-spoort		Thick dolomites with overlying shales	Major groundwater supplies at Kurman and Mafeking	Protect wellfields from polluting activities
		Ventersdorp	Interbedded lavas and tuffs	Low groundwater potential in shallow weathered and fractures horizons; Drought susceptible	Allow only small scale groundwater dependency
		Witwatersrand	Interbedded quartzites, shales, gold bearing conglomerates and diamictites	Goldmines – major dewatering problems from overlying dolomite compartments	Conceptual flow modelling and numerical modelling
	Dominion		Volcanics and sediments metamorphosed to greenschist-amphibolites	Low yields vulnerable to pollution	Protect small scale rural supplies from pollutant sources
	Quaternary	Achaean	Granite-greenstones	Low groundwater potential in shallow weathered and fractures horizons; Low yields vulnerable to pollution	Protect small scale rural supplies from pollutant sources

4. Conclusions

The Orange-Senqu River basin spans a range of environments from the highland headwaters through the savannah plains of much of South Africa into the semi-arid and arid lands of Botswana and Namibia. As such, the importance of the role of groundwater increases towards dryer lands in the west where groundwater becomes the only safe source of water for drinking water supply. It is also needed to sustain dry land agricultural activity, industry, notably mining, and most other uses as surface water may only be available during wet climate cycle years. These diverse environments challenge the management of the overall river basin and require different emphases in different parts of the Orange-Senqu River basin. Nevertheless, a uniform basin-wide approach to groundwater management is essential to ensure the optimum sustainable use of the available groundwater resources.

The key to the future management of the Orange-Senqu River basin lies in international collaboration, data and knowledge sharing and on-going dialogue between the four neighbouring states that occupy the basin. This is perhaps the hardest part of the activities that will be needed to ensure best practice in the basin, but is nevertheless fundamental to success. The management issues fall broadly into two groups, the physical measuring, monitoring and understanding of the groundwater systems in the basin, and the issues relating to the basin-wide governance of the basin and oversight of its management for the benefit of all its people. None of these issues are insurmountable but all will need a concerted effort to overcome and will require considerable enabling resources. Investment in the development of shared and owned management strategies are compelling provided the vision of a unified basin management scheme is adhered to.

As this move towards holistic and uniform groundwater management in the basin proceeds it is also very apparent that individual technical solutions need to be developed for individual problems. For example, solutions for pollution incidents in the Karoo sediments need to be different from those in the rapid groundwater throughflow systems in the karst dolomite aquifers, whereas the interaction between surface and groundwater might be critical in alluvial aquifers. On a spatial basis, solution of the village level contamination of shallow aquifers is needed in Lesotho, while in South Africa increasing demand vies with serious pollution issues which require detailed hydrogeological investigation over large areas, in Botswana rapid infrastructure development has stressed available groundwater in storage and new resources need to be developed, water quality is also a problem with widespread salinity in the Kalahari beds, and in Namibia water scarcity in general needs to be tackled by a complete understanding of the available resources. Each of these solutions will require specific underpinning studies to facilitate their development and adoption.

The major unresolved question in many of the aquifers in the Orange-Senqu River basin is the estimation of recharge. This is currently being addressed at a range of levels and through a variety of approaches. These activities should remain a focus of study in the basin because the reliable estimation of recharge is the key to the sustainable management of the available groundwater resources.

It is apparent that the key constraints to all these technical solutions are resources (both human and financial) and uniformity of approach across the river basin as a whole, coupled with enhanced dialogue and information sharing between basin states. If these constraints can be removed, or even diminished, then the future for sustainable groundwater management in the Orange-Senqu River basin will be bright.

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Annex: Transboundary aquifers

Cobbing et al. (2008) focus on the TBAs that border South Africa and conclude:

"Based on this study of South African transboundary aquifers, it is proposed that the traditional understanding of transboundary groundwater issues as a potential source of conflict be modified. For most of the length of South Africa's border, potential dispute over transboundary groundwater is not a major concern. In general, transboundary aquifers such as the 'Coastal Sedimentary Basin' or the 'Karoo Sedimentary Aquifer' (Struckmeier et al. 2006) are potentially misleading in terms of the level of management required. Given the sparse data on southern African transboundary aquifers and the relatively low levels of technical co-operation between the riparian states, the region would be better served by using transboundary groundwater as a vehicle to improve technical cooperation, data sharing, training and research..."

The TBAs in the Orange-Senqu River basin involve low flow volumes with little potential for surface or groundwater resource degradation across a political border. There are three TBAs within the basin:

South West Kalahari/ Karoo Basin Aquifer (Botswana; Namibia; South Africa):
Thick Kalahari Beds sands, calcretes and clays confine productive Lower Karoo sandstones interbedded with mudstones, shales and coals. In Namibia, the Lower Karoo Stampriet Aquifer is a major source of water for domestic and agricultural use. Little development of this aquifer has been made in south western Botswana or the adjacent part of South Africa. Large parts of these areas have been demarcated as National Parks. However, over-abstraction in Namibia may have caused a reduction in natural flow into areas of South Africa and Botswana within this aquifer.

Zeerust - Ramotswa - Lobatse Dolomite Basin Aquifer (Botswana; South Africa):
The Precambrian Transvaal Cherty Dolomite forms an arcuate karstic aquifer between Zeerust, Ramotswa, Lobatse and Mafikeng. Natural cross border flow and degradation are unlikely as groundwater occurs in a series of isolated basins. There is a minor risk of localised cross-border pollution.

Karoo Sedimentary Aquifer (Lesotho; South Africa):
The Karoo Stormberg and Transvaal groups include mudstones, siltstones and sandstones with dolerite intrusions. The transmissive properties of these rocks depend on fracture flow and borehole yields are generally < 0.5 l/s. Cross-border flow in the more transmissive semi-confined and confined aquifer units is low.