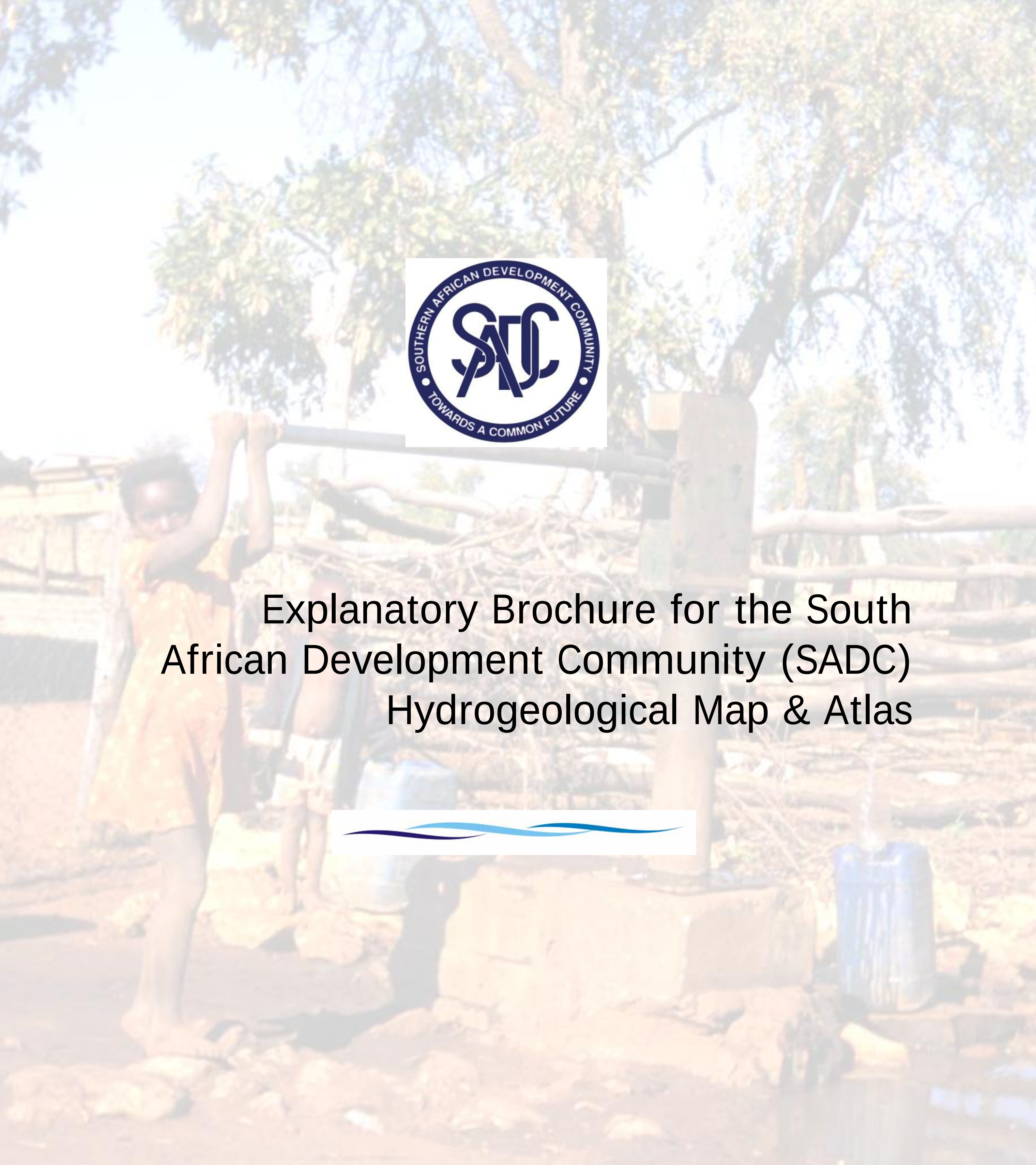

Explanatory Brochure for the South African Development Community (SADC) Hydrogeological Map & Atlas

Technical Assistance to the Southern Africa Development Community (SADC) - "SADC Hydrogeological Mapping Project"

Explanatory Brochure for the South African Development Community (SADC) Hydrogeological Map & Atlas

The brochure is available in French and Portuguese.

31 March 2009

A report to the Southern African Development Community (SADC) and Cooperating Partners:

European Union and GTZ

Project Implementation Unit:

Phera Ramoeli
Senior Programme Officer
SADC Infrastructure and Services Directorate – Water Division

Thomas Farrington
Advisor to the Regional Authorising Officer, European Union Development Fund

Peter Qwist-Hoffmann
Capacity Development Advisor
GTZ Transboundary Water Management in SADC

Othusitse Katai
SADC Hydrogeological Mapping Project Manager
SADC Infrastructure and Services Directorate – Water Division

Oteng Lekgowe/Magowe Magowe
Hydrogeologists
Department of Geological Survey, Botswana

Consultants:

Sweco International (Sweden)
Water Geosciences Consulting (South Africa)
Council for Geosciences (South Africa)
Water Resources Consultants (Botswana)

Foreword: Southern African Development Community (SADC)

The development and management of water resources in the SADC Member States has traditionally focused on surface water despite the fact that groundwater is widely used for both domestic and commercial water needs in the regions rural villages. Recognising the increasing dependency and reliability on groundwater resources as a result of increasing aridity and limited surface water resources, the SADC ministers responsible for water initiated a coordinated effort for sustainable development and long-term security of groundwater resources within the Southern African region way back in November 1995. This initiative led to the development and approval of a Regional Groundwater Management Programme for the SADC Region that consists of a framework of 8 Programmes and 10 proposed projects for implementation within the overall framework of regional co-operation and development. One of the components from the Regional Groundwater Management Programme identified as a priority was the preparation of a Regional Hydrogeological Map.

The SADC region is aware of threats to our groundwater resources posed by increasing population pressures, industrial development, mining, point and non-point sources of pollution and agricultural practices that result in over-exploitation, contamination, and degradation of the resources. Incidences of inappropriate land development or utilisation that has inadvertently contaminated important aquifers in the region can be listed, largely because groundwater is an invisible resource. The hydrogeological map produced by this project will readily give understandable visual representation of the region's groundwater resources, therefore assisting in better planning and management.

There are other initiatives complimenting this project such as the regional Groundwater Drought Management Project that aims to empower persons and organisations involved in the management of groundwater in the region to minimize and/ or mitigate against the effects of groundwater drought through the development of a regional SADC Groundwater Vulnerability Map that will provide tools for water managers and policy makers to support the sustainable management and mitigation of groundwater drought. The new Geological Map of the SADC region on a scale of 1: 2 500 000 has been compiled and is awaiting publication; which formed a base for the current interactive, web-based SADC Hydrogeological Map and Atlas; now online.

The EC-SADC Regional Strategy Paper (RSP) for the ninth EDF 2002-2007 reflects the EC's willingness to support SADC in promoting Regional Integration and Trade as well as the region's smooth integration into the world market and other key elements of the SADC Regional Indicative Strategic Development Plan (RISDP). The SADC Extra-Ordinary Summit on Agriculture and Food security, held in Dar-es-Salaam on 15 May 2004, called for accelerated implementation of transboundary water resources development and management policies and programmes and; to facilitate inter-basin water transfers within the Framework of the SADC Revised Protocol on Shared Watercourses. From the effective planning and implementation perspective of this Directive, there is nothing better than the availability of the region's hydrogeological map.

Those who will read this brochure will get a broader perspective of the nature and configuration of the region's groundwater systems, hydrogeological concepts applied and how the web-based map should be read and understood. One must hasten to say hydrogeological mapping is a process that continuously needs to be updated as and when new information and data becomes available. We as a region have just embarked on that, and there is still a lot to be done if we are to realise the full benefit of routinely deriving and storing hydrogeological information in an array of different digital mechanisms such as geographical information systems, relational databases, groundwater flow models, image processors, statistical packages and surface interpolators.

In my concluding remarks, I would like to thank all the SADC Member States who actively participated in this project and remind the rest to utilise this piece of information for planning and management of our valuable groundwater resources. My gratitude also goes to our Cooperating Partners, in particular the

European Union and GTZ for making this a success, the Department of Geological Survey (Implementing Agency) Botswana for providing all the management, technical and material support that was not covered by the Cooperating Partners and the Consultant (SWECO International and consortium members; Council for Geoscience - South Africa, Water Resources Consultants - Botswana and Water Geosciences Consulting – South Africa) for remarkably doing well in delivering the products under a very tight project schedule

All this was done under an effective coordination by the Directorate of Infrastructure and Services – Water Division, as it strives to implement the Regional Strategic Action Plan on Integrated Water Resources Development and Management (RSAP-IWRDM) in its endeavour to contribute towards the achievement of the Millennium Development Goals (MDGs) in the SADC Region.

Remigious Makhumbe
Director, Infrastructure and Services
SADC

Foreword: Department of Geological Survey, Botswana

"...And it never failed that during the dry years the people lost forgot the rich years, and during the wet years they lost all memory of the dry years. It was always that way."

East of Eden, John Steinbeck, 1952.

The above statement reflects the high variability in our climate and consequently the rainfall pattern in most SADC countries. We can no longer wait helplessly in anticipation that next year will bring good rains. There is therefore a greater need to ensure a constant water supply through the dry and the wet years. Groundwater comes in handy in this respect but to date little or no work has been carried out to try to understand it at a SADC scale.

Following this contribution of SADC to the understanding of this most precious resource within the Sub-region. It goes without saying that if we are to make the best use of the groundwater resource then it is critical that we must first understand its occurrence. Although the SADC-Hydrogeological Map at a regional scale, it is still an important management tool and a step in the right direction. Because groundwater knows no political boundaries, this project gives the SADC member states a golden opportunity not only to know what happens beyond the borders of each member state through data and knowledge sharing but also to learn from each other. It is with much enthusiasm and anticipation that this product will go a long way towards providing a suitable environment for regional, technical cooperation. Together, SADC member states can share, co-develop, co- exploit, co-manage the groundwater resource and this will in effect enable them to cooperate and avoid water related conflicts.

The Production of the SADC Hydrogeological map was not without challenges. The completion of the map means that we have all endured and overcome. Among the challenges encountered was the issue of data availability and quality where submitted. In this regard the Production of the SADC Hydrogeological map has been an eye opener for most of us and the lessons thereof shall be assimilated into our daily operations.

The Department of Geological Survey would like to express its gratitude and confidence shown by the SADC Member Sstates for giving it the responsibility of being the implementing agency. We have derived much benefit from the whole exercise we shall also host the product with dedication as agreed upon.

Pelotsheweu Phofuetsile
Deputy Director, Hydrogeology
Department of Geological Survey, Botswana

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The Southern African Development Community (SADC) hydrogeological map has been in planning since the early nineties. Numerous persons have been involved in the conceptualisation of the SADC hydrogeological map, since those days, and their contributions to the project are gratefully acknowledged.

We express our gratitude to the Project Steering Committee members of the Member States for their input during the course of the consultancy. In particular, the project team acknowledges their time and effort in making data and information available for use in the compilation in the SADC hydrogeological map.

The project team is grateful to the country participants who has supported the project and enthusiastically participated in the activities of the programme. Their participation at national workshops to edit and review the map resulted in invaluable comments. Ms Helene Mullin from the Department of Water Affairs, South Africa are acknowledged for her efforts to arrange the first capacity-building workshop in Pretoria on hydrogeological mapping.

The project team was hosted by the Department of Geological Survey in Lobatse, Botswana. We are grateful to our counterparts Oteng Lekgowe, Magowe Magowe, Pelonomi Matlotse, Keoagile Kgosiesele and Charles Chibidika for their participation in the project. Their eagerness and interest in the project was most welcome.

The SADC Project Manager, Mr O Katai, is thanked for his wise leadership throughout the consultancy. His input has been invaluable at times. The SADC Infrastructure and Services Directorate – Water Division is also thanked for their contribution to the project. We are grateful to the European Union and GTZ for their financial support to the project.

Dr. Kevin Pietersen (Water Geosciences Consulting)
Dr. Nils Kellgren (Sweco)
Ms. Magda Roos (Council for Geoscience)
Mr. Paul DeVries (Sweco)
and
Dr. Luc Chevallier (Council for Geoscience)

SWECO

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List of main authors

K. Pietersen	Team Leader/Hydrogeological expert
N. Kellgren	Project Director/Remote Sensing -GIS expert
M. Roos	Cartographer
P. DeVries	Database management specialist

List of Short term experts

L. Chevallier	Geologist
M. Karen	Hydrogeologist
H. Saeze	Hydrogeologist

List of Contributors

T. Bakaya	Water Resources Consultants, Gaborone, Botswana
L. Chevallier	Council for Geoscience, Cape Town, South Africa
J. Cobbing	Water Geosciences Consulting, Pretoria, South Africa
P. DeVries	Sweco, Gothenburg, Sweden

T. Forsmark	Sweco, Gothenburg, Sweden
F. Hartzer	Council for Geoscience, Cape Town, South Africa
M. Karen	Private consultant, Gaborone, Botswana
N. Kellgren	Sweco, Gothenburg, Sweden
M. Liedholm	Sweco, Gothenburg, Sweden
P. Macey	Council for Geoscience, Cape Town, South Africa
K. Pietersen	Water Geosciences Consulting, Pretoria, South Africa
M. Roos	Council for Geoscience, Pretoria, South Africa
H. Saeze	Council for Geoscience, Pretoria, South Africa
P. Seman	Sweco, Stockholm, Sweden
K. Witthüser	Water Geoscience Consulting, Pretoria, South Africa

1. Introduction

"*Groundwater is a hidden treasure, often under our very feet, but little recognised and acknowledged for the strategic role it plays. I have called it the hidden treasure - though we may not be able to see it, yet it provides life-giving water to people and ecosystems across the globe. It is, truly, blue gold, a resource that must be used wisely to ensure sustainable livelihoods for millions of people*"

Ronald Kasrils, 2003

1.1. The SADC hydrogeological map and atlas

The SADC hydrogeological map and atlas provides an overview of the groundwater resources of the SADC region by means of an interactive web-based regional map. This explanatory brochure accompanies the SADC hydrogeological map and atlas.

The map is a first, but necessary, step to support groundwater resource planning at multi-national level as well as regional trans-national scales.

The preparation of a regional hydrogeological map was identified as a priority in SADC. This resulted in the inclusion of the project as a component of the Regional Groundwater Management Programme in the Regional Strategic Action Plan for Integrated Water Resources Development and Management (Box 1 and 2).

Hydrogeological maps deal with water and rocks and their interrelationships. Two distinct groups of hydrogeological maps can be defined (Struckmeier and Margat 1995):

- General hydrogeological maps and groundwater systems maps associated with reconnaissance or scientific levels are suitable tools to introduce the importance of water (including groundwater) resources into the political and social development process;
- Parameter maps and special purpose maps are part of the basis of economic development for planning, engineering and management; they differ greatly in content and representation according to their specific purpose. An example of a special purpose map would be one which shows areas of highly protected groundwater resources, used for waste disposal planning.

The SADC hydrogeology map is a general hydrogeological map. It provides information on the extent and geometry of regional aquifer systems. The map is intended to serve as a base map for hydrogeologists and water resource planners, whilst at the same time presenting information to non-specialists. Thus, the map is a visual representation of groundwater conditions in SADC on a general scale. The map serves as a starting point for more detailed regional groundwater investigations by showing current data and knowledge gaps[1].

The SADC HGM map is not intended to replace:

- National groundwater maps
- Borehole siting tools and methods
- Site-specific investigations

[1] Figure redrawn from http://www.lockyerwater.com/doc/cartoon_09.jpg

Box 1: Regional Strategic Action Plan on Integrated Water Resources Development and Management (RSAP-IWRM). Annotated Strategic Action Plan 2005 – 2010

The mission of the RSAP-IWRM is *"to provide a sustainable enabling environment, leadership and coordination in water resources strategic planning, use and infrastructure development through the application of integrated water resource management at Member State, regional, river basin and community level"*.

Four strategic areas are identified:

- Regional Water Resources Planning and Management
- Infrastructure Development Support
- Water Governance
- Capacity Building

A number of projects are distributed within the strategic areas. For example, the area focussing on Regional Water Resource Planning and Management has the following projects:

- RWR 1: Consolidation and Expansion of SADC HYCOS
- RWR 2: Standard Assessment of Water Resources
- RWR 3: Groundwater Management Programme in SADC
- RWR 4: Support for Strategic and Integrated Water Resources Planning
- RWR 5: Dam Safety, Synchronisation and Emergency Operations

Box 2: Groundwater Management Programme in SADC (ten projects listed in order of priority)

1. Capacity Building within the Context of Regional Groundwater Management Programme
2. Develop Minimum Common Standards for Groundwater Development in the SADC Region
3. Development of a Regional Groundwater Information System
4. Establishment of a Regional Groundwater Monitoring Network
5. Compilation of a regional Hydrogeological Map and Atlas for the SADC Region
6. Establish a Regional Groundwater Research Institute/Commission
7. Construct a Website on Internet and publish quarterly News letters
8. Regional Groundwater Resource Assessment of Karoo Aquifers
9. Regional Groundwater Resource Assessment of Precambrian Basement Aquifers
10. Groundwater Resource Assessment of Limpopo/Save Basin

1.2. The consultancy

The compilation of the SADC hydrogeological map took place during the period 1 June 2009 to 31 March 2010. The consultancy was awarded to a consortium consisting of Sweco International (Sweden), Council for Geoscience (South Africa), Water Geosciences Consulting (South Africa) and Water Resources Consultants (Botswana). Sweco was the lead consultant.

The project implementation agent (PIA) was the Department of Geological Survey (DGS), Botswana.

The overall objective of the project was to improve the understanding of groundwater occurrence within the SADC region and to promote cooperation and better understanding of water resource planning and management.

The project had to produce the following two main priority results:

- Comprehensive, interactive web-based hydrogeological map of the SADC region;
- Enhanced institutional capacity for producing and using hydrogeological maps in water resources planning, development and management

1.3. Role of groundwater

Economic growth and poverty reduction in the Southern African Development Community (SADC) requires that all potential water resources are appropriately protected and utilised. Groundwater is a significant resource in the region but has been neglected in management. Hence, its value has been understated. However, there is growing recognition as evidenced by statements such as by former Minister of Water Affairs in South Africa, Ronnie Kasrils and others about the fundamental importance of better governance of the resource for the benefit of current and future generations. This awareness and recognition by political leaders has led to the establishment of the Groundwater Commission under the auspices of the African Ministers Council on Water.

The role of groundwater in the region includes:

- meeting the domestic water supply requirements of a significant percentage of the population;
- supplying urban towns and cities with water;
- contributing to water security during drought conditions;
- achieving food security for households; and
- maintaining environmental functions

In particular, its contributions to rural livelihoods are immeasurable (Box 3).

Box 3: A Garden In the Heart of the Village (By Nicholas Mokwena & Terna Gyuse)[i]

Look, there's no drama with the borehole in Mokobeng. And that's the way it should be.
....
In the heart of the village there is a garden measuring about 50 metres square. Here a group of women have joined hands to alleviate poverty.

The Ngwaoboswa Conservation Group is a group of volunteers who are making use of the village garden to grow vegetables, fruits and keep bees. They grow green pepper, spinach, tomatoes, butternuts, watermelons, orange, mango and rape. Each season they plant vegetables and fruits suitable for that particular season.

See the Ngwaoboswa chairperson here. Mmandaba Makola, you say the garden is watered from the village borehole.

"For our garden we use the hosepipe and watering can for watering. We use groundwater. It is the only source of water in our village. It is able to sustain our watering.
....
When everything is ready for harvesting, the fruits and vegetables are sold at a reasonable price. Most customers are the villagers and sometimes customers are drawn from neighbouring villages.

The group shares the profit every month end. Some of the money is kept to be used when the need arises. The project start up has been funded by United Nations Development Programme (UNDP), but now it must carry itself.

Sis' Makola, you as Ngwaoboswa women also assist in the village with food.

"Yes, this project is not only about making profit. We sometimes donate the vegetables to the community home-based care. Whenever there is a function in the village main kgotla, primary or secondary school we contribute with these vegetables and fruits."

1.4. Groundwater occurrence

Rainwater moves slowly downwards to replenish the groundwater resource, in a process called "recharge". It can take many years for infiltrating rainwater to reach the groundwater level or water table.

All water found underground is not groundwater. Groundwater is the subsurface water below the unsaturated zone (Figure 1). The unsaturated zone is the portion of the Earth between the land surface and the saturated zone. The saturated zone encompasses the area below the water table in which all interconnected openings within the geologic medium are completely filled with water.

Groundwater naturally discharges as springs and as baseflow to rivers.

Groundwater is usually accessible by means of wells or boreholes. Natural groundwater quality is usually good, and it can often when unaffected be pumped into supply systems with little or no treatment.

Groundwater is resistant to droughts compared to surface water and can maintain a water supply even when dams and rivers have dried up.

Whilst groundwater technically can be found in most places, only some groundwater resources are valuable to man. These are called aquifers, which yield enough water to be useful.

The study of water flow in aquifers and the characterisation of aquifers are called hydrogeology

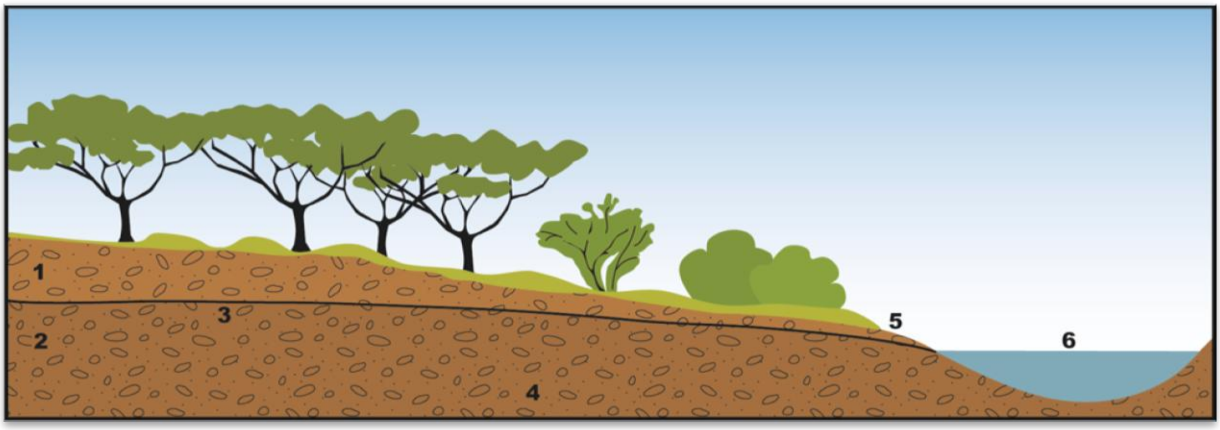


Figure 1: Diagram to illustrate the occurrence of groundwater[ii]
(1 unsaturated zone, 2 saturated zone, 3 water table, 4 groundwater, 5 land surface, and 6 surface water)

2. People and groundwater

"The African population without access to improved drinking water sources increased by 61 million between 1990 and 2006, from 280 million to 341 million. Increases in coverage are not keeping pace with population growth"

(UNICEF and World Health Organization 2008)

2.1. Access to water

The present population of SADC stands at about 250 million people. Between 90 and 100 per cent of the population of Botswana, Namibia, Mauritius and South Africa have access to improved drinking water sources, whilst in Lesotho, Zimbabwe and Malawi access is between 75 and 90 per cent (Figure 2). Angola, Swaziland, Tanzania and Zambia have access figures of between 50 and 75 per cent. The Democratic Republic of the Congo (DRC) and Madagascar are lagging behind with access of less than 50 per cent. There are, as expected, disparities in access to improved water resources between urban and rural areas (Figure 3) and (Box 4). A number of SADC countries are likely to meet the Millennium Development Goal (MDGs) drinking water target.

> The widespread development of groundwater is the only affordable and sustainable way of improving access to clean water and meeting the Millennium Development Goals for water supply by 2015.
>
> Alan M. MacDonald, Jeff Davies and Roger C. Calow

2.2. Opportunities for groundwater

By all accounts only a small percentage of available groundwater resources are used. Unfortunately, no reliable statistics of groundwater use are available. Nonetheless, a significant amount of groundwater remains untapped creating opportunities for further judicious use in:

- Rural water supply
- Urban water supply
- Water security
- Food security
- Environmental services

2.2.1. Rural water supply

Already, most rural communities in SADC are served from groundwater resources. Access to the resource is one of the critical factors ensuring sustainable livelihoods and by implication human well-being in the region. Groundwater has great potential to serve even more communities, particularly in those areas where large bulk water infrastructure does not exist and arid conditions prevail.

About 75 per cent of the Mozambican population relies on groundwater resources. Similarly a significant number of rural communities in Angola are dependent on groundwater resources with groundwater the main source of drinking water outside the larger towns. The same applies to Zambia. In DRC more than 90 percent of the rural population relies on groundwater resources. Botswana and Namibia are even more reliant on groundwater resources due to the scarcity of surface water (Figure 4)

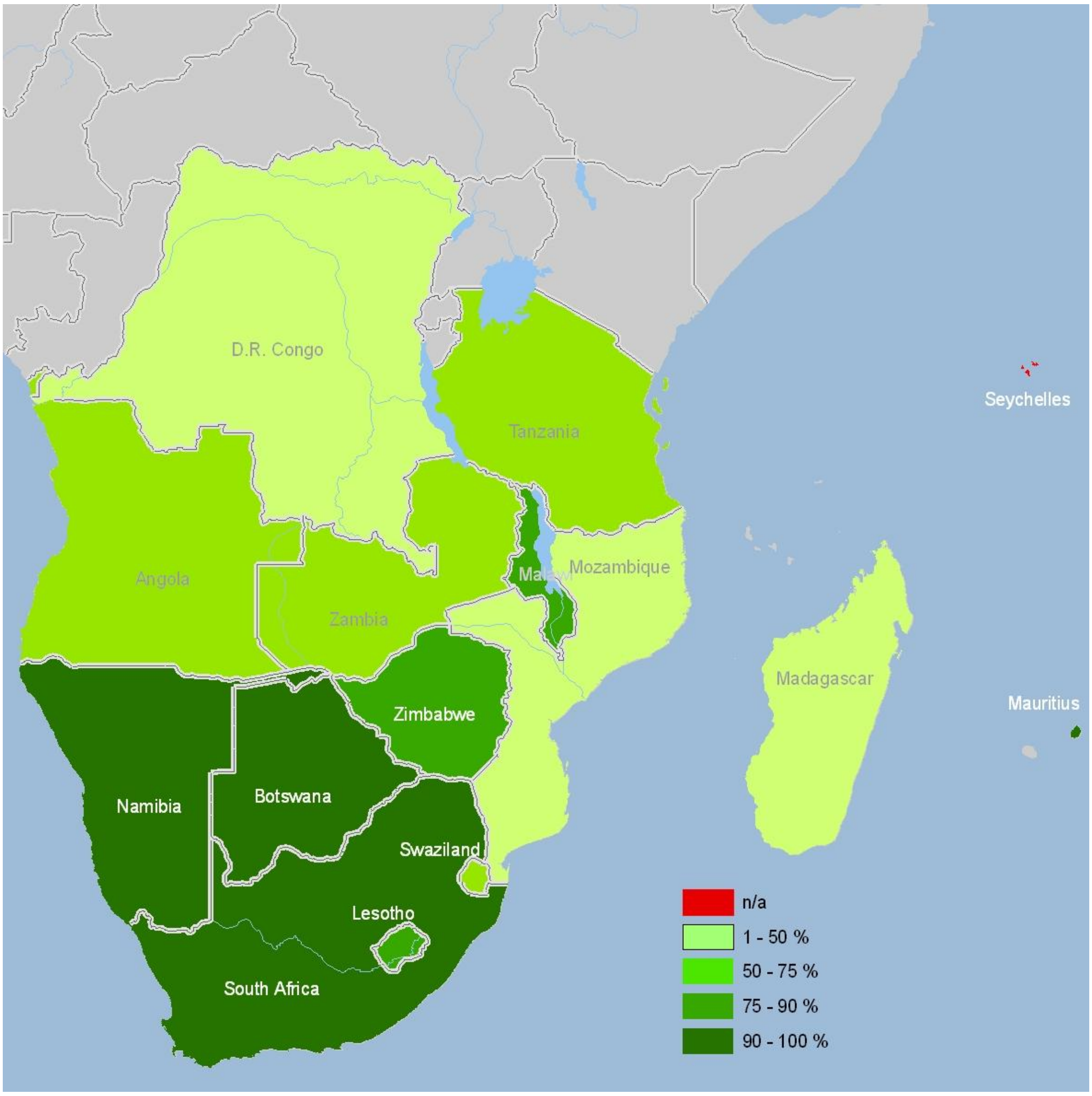


Figure 2: Percentage of population with improved drinking water sources in SADC. (UNICEF and World Health Organization 2008)

Box 4: Disparities between urban and rural drinking water coverage[iii]

Urban drinking water coverage in SADC is 86 per cent

- Since 1990, 37 million people in urban areas have gained access to an improved drinking water source
- Of the 95 million people in urban areas, 50 per cent has a piped connection on premises, up from 36 per cent in 1990.
- Since 1990, the urban population without access to an improved drinking water source increased by 7 million people to 13 million people in 2006

Rural drinking water coverage in SADC is 47 per cent

- Since 1990, 32 million people in rural areas gain access to an improved drinking water source
- Of the 157 million people in rural areas, 13 million have a piped connection on premises while 62 million use other improved drinking water sources.
- Since 1990, the rural population without access to improved drinking water sources increased by 21 million people to 83 million people in 2006

Source: (UNICEF and World Health Organization 2008)

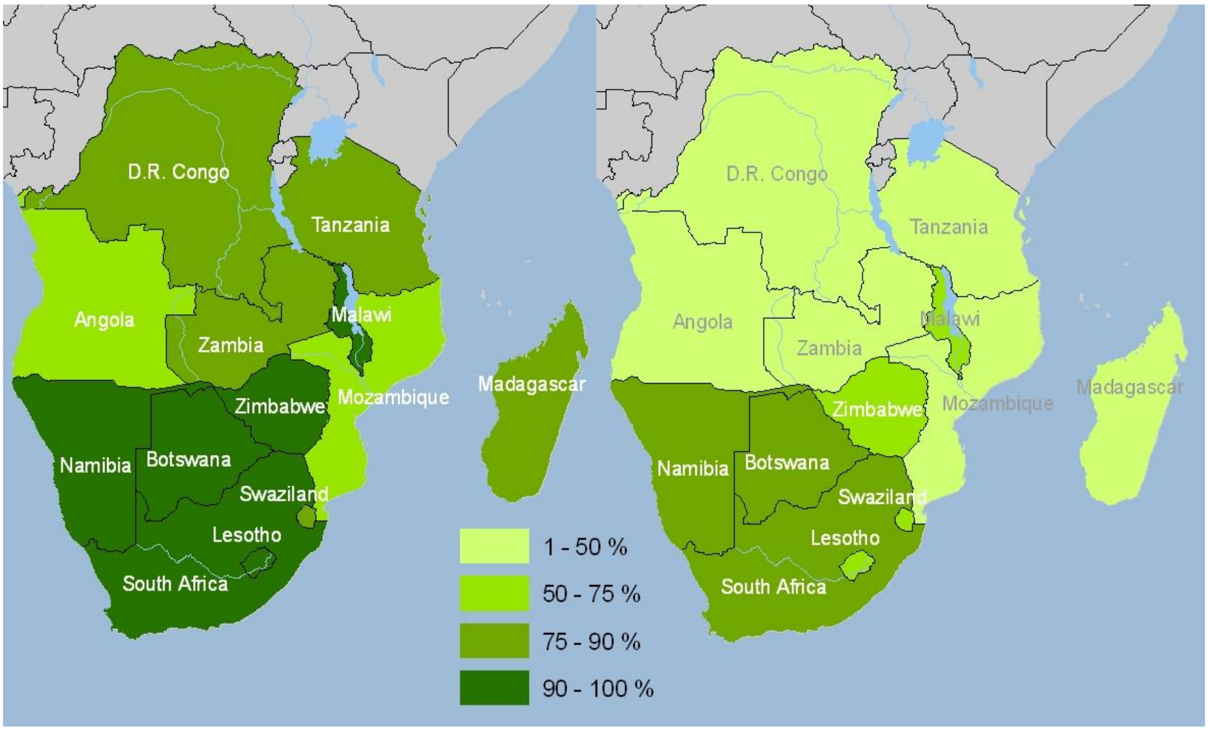


Figure 3: Urban (figure on the left) /Rural (figure on the right) disparity with the percentage of population with improved drinking water sources in SADC. (UNICEF and World Health Organization 2008). Mauritius and Seychelles are not depicted due to the scale of the maps.

Figure 4: Communities reliant on a hand dug well, in the north of Namibia in Onaimbungu. *(Photograph courtesy of Harald Zuter)*

2.2.2. Urban water supply

Whilst the value of groundwater for rural water supply purposes is recognised, its role in urban water supply purposes cannot be neglected. For example, the City of Tshwane in South Africa obtains a significant portion of its water supply from boreholes and springs, which is blended with surface water within the bulk distribution system (Figure 5). Lusaka, the capital of Zambia, obtains 40 to 50 per cent of its water requirements from groundwater resources. Current abstraction of groundwater in Lusaka is estimated to be between 50 and 65 million m^3/annum. Dodoma, the capital city of the United Republic of Tanzania, mainly depends on groundwater. Groundwater has played a crucial role during drought periods in Bulawayo, the second largest city in Zimbabwe.

There are opportunities for further use of groundwater resources in urban areas.

Figure 5: Pretoria fountains, which supply approximately 10 per cent of the water supply of the City of Tshwane in South Africa *(Photograph courtesy of Jeff Davies).*

2.2.3. Water security

It is widely recognised that developing and managing water resources to achieve water security remains at the heart of the struggle for growth, sustainable development and poverty reduction. Conjunctive use of surface and groundwater resources refers to the coordinated operation of a groundwater basin and a surface water system to increase total water supplies and enhance total water supply reliability. Conjunctive use relies on the principle that by using surface water when it is plentiful, recharging aquifers and conserving groundwater supplies in wet years, water will then be available for pumping in dry years. In the case of Windhoek, the capital of Namibia, groundwater contributes about 10 per cent of the water supply. A system of artificially recharging groundwater resources has been put in place. The aim is to make available up to 8 million m^3/annum of groundwater for abstraction. The current Windhoek water demand is about 20 million m^3/annum. The town of Atlantis in South Africa has further enhanced its water supplies through artificial recharge. The feasibility of artificial recharge has also been demonstrated in hard rock environments (Figure 6).

The further expansion of artificial recharge schemes throughout SADC requires investigation.

Figure 6: Setting up an artificial recharge scheme in basement aquifers *(Photograph courtesy of Ricky Murray)*

2.2.4. Food security

An important component of agricultural policies in the region is to increase incomes of the poorest groups in society through opportunities for small to medium-scale farmers. Most of these farmers will be totally dependent on groundwater for domestic and agricultural use. The advantage of using available groundwater resources for irrigation is that it is able to mitigate the effects of drought and erratic rainfall on agricultural production.

A further advantage of the reliability of water supplies is that there is a multiplier effect on yields as water is delivered at critical points during plant growth. Groundwater is useful for small-scale irrigation due to its proximity and the relatively small investments needed to access it.

In Angola groundwater irrigation is important in areas where the rainfall is not sufficient for crops and where rivers are unreliable. Groundwater irrigation is also important in the coastal areas and in the south-western provinces of Angola. Shallow groundwater resources are particularly suitable for use by farmers, since access costs are relatively low. In Zimbabwe, alluvial aquifers associated with the Shashani River, a tributary of the Limpopo River, supply water to a number of irrigation schemes (Figure 7).

Figure 7: Garden irrigated from alluvial groundwater, Shashani River, Zimbabwe *(Photograph courtesy Richard Owen)*

2.2.5. Environmental services

Many ecosystem services have a direct linkage with groundwater storage, recharge and discharge. However, the interdependencies between ecosystem services and groundwater are poorly understood and recognized.

During drought conditions the Lake St Lucia estuary on the east coast of South Africa experiences high salinities, with values above that of seawater. Groundwater flowing into the estuary from prominent sand aquifers along its eastern shoreline supports low-salinity habitats for salt-sensitive biota until conditions regains tolerable salinity (Taylor, et al. 2006).

Wetlands are frequently groundwater discharge zones. For example Lake Sibaya in KwaZulu-Natal is dependent on nearby aquifers. The interaction between surface water and the groundwater strongly influences the structure and function of the Okavango wetland ecosystem in north-western Botswana. The cycling of seasonal flood water through the groundwater reservoir plays a key role in creating and maintaining the biological and habitat diversity of the wetland, and inhibits the formation of saline surface water (McCarthy 2006). In the Namib Desert springs allow vegetation and wildlife to flourish in certain areas.

2.3. Groundwater challenges

2.3.1. Pollution

Groundwater supplies are increasingly threatened with contamination by various sources. For example, the coal mining industry in South Africa is a mature industry with large numbers of closed collieries. Although a number of these collieries closed some time ago, no rehabilitation or remediation has taken place. Pollution of groundwater includes acidification and increased concentrations of pollutants such as sulphates and heavy metals. Similarly, over the past decade or so many gold mines in the Gauteng region of South Africa have closed, and dewatering operations have ceased. In the abandoned mining areas the consequent rebounding water table has led to significant pollution of groundwater by acid mine drainage (AMD). AMD is a result of the oxidation of metal sulphides, and is characterised by elevated heavy metal concentrations, high sulphate contents, an increased electrical conductivity and a lowering of the pH of the water in the mining area. It can also lead to pollution by radioactive materials.

Similar pollution challenges from mining activities are being experienced in Zambia (Figure 8) and DRC.

Figure 8: Cobalt laden discharges emanating from ore processing activities, Copperbelt, Zambia. *(Photograph courtesy Björn Holgersson)*

In urban areas the indiscriminate use of chemicals and generation of wastes at both domestic and industrial level tend to concentrate potential sources of contamination. Poor sanitation services are polluting groundwater resources in Lusaka and other areas (Figure 9). Agriculture is the biggest user of groundwater and also contributes to diffuse contamination. Nitrate is the most common agricultural contaminant and pesticides and herbicides are likely to be a problem in some areas.

Figure 9: Poor sanitation services *(Photograph courtesy of David Gadd)*

2.3.2. Poor natural groundwater quality

Human health can be affected by long-term exposure to either an excess or a deficiency of certain constituents in groundwater. In particular, fluoride levels in drinking water higher than 1.5 mg/ℓ may cause significant health problems such as fluorosis. This is a bone disease that in its mild form results in mottling of teeth. There are large parts of SADC that have high fluoride concentrations in the groundwater. The high concentrations are a function of various factors such as the availability and solubility of fluoride minerals, concentration of calcium and pH amongst others.

2.3.3. Over-abstraction of groundwater resources

Over-abstraction of groundwater is causing declining water levels in some areas of SADC. This is often due to irrigation. The Dendron basement aquifer is a classic example of over-abstraction of groundwater resources in South Africa. Water levels have dropped more than 50 metres in the last 30 years. In the Tosca Molopo area on the Botswana-South Africa border abstraction from high yielding deep boreholes has led to water levels declining 10 to 20 m regionally and up to 60 m locally due to intensive irrigation. The lack of management of groundwater resources is also evident in community water supplies, where in some cases groundwater resources are developed unsustainably. This leads to resource failure and puts communities at risk.

2.3.4. Drought and climate change

Although predicting climate change impacts is complex, uncertainties surrounding our predictions are gradually diminishing as international Global Climate Models continue to improve, and suitable techniques for downscaling such predictions, from global down to regional and catchment scales, continue to be developed and refined. Predictions for southern Africa include increases in temperature and potential evaporation (evapotranspiration) rates, shifts in precipitation patterns, an increase in the frequency of flooding and droughts, and, in coastal areas, sea level rise. The implications for groundwater are unknown but may be considerable such as reduced recharge, seawater intrusion due to sea-level rise and increased groundwater over-abstraction.

2.3.5. Operation and maintenance

The failure of groundwater supply schemes is often blamed on the resource rather than on the infrastructure associated with the resource (Figure 10). Boreholes may fail because of the:

- High ratio of people to a borehole, in many cases
- Misuse of pumps
- Inappropriate pump regimes
- Poor rate of payment for services.
- Many of the pumps are located in remote and scattered places, which in turn complicate access; maintenance thus takes place on an irregular basis.
- Maintenance and cost differ from place to place depending on the availability of spare parts and technicians, resulting in irregular maintenance.
- Community participation is poor and those residents who are dissatisfied with water regulations may even damage water systems

Figure 10: Borehole suffering from lack of O&M – diesel spillage and cracked concrete block *(Photograph courtesy Karabo Lenkoe)*

3. Natural Environment

"We never know the worth of water till the well is dry.

Thomas Fuller

3.1. Geology

3.1.1. Overview

The nature of the rock, the degree of consolidation and the fracturing plays a primary role in the presence and the type of aquifer present.

The SADC region has a varied and complex geological history. To understand the historical development and the relationship of geological events geologist use a geologic time scale (Figure 11)

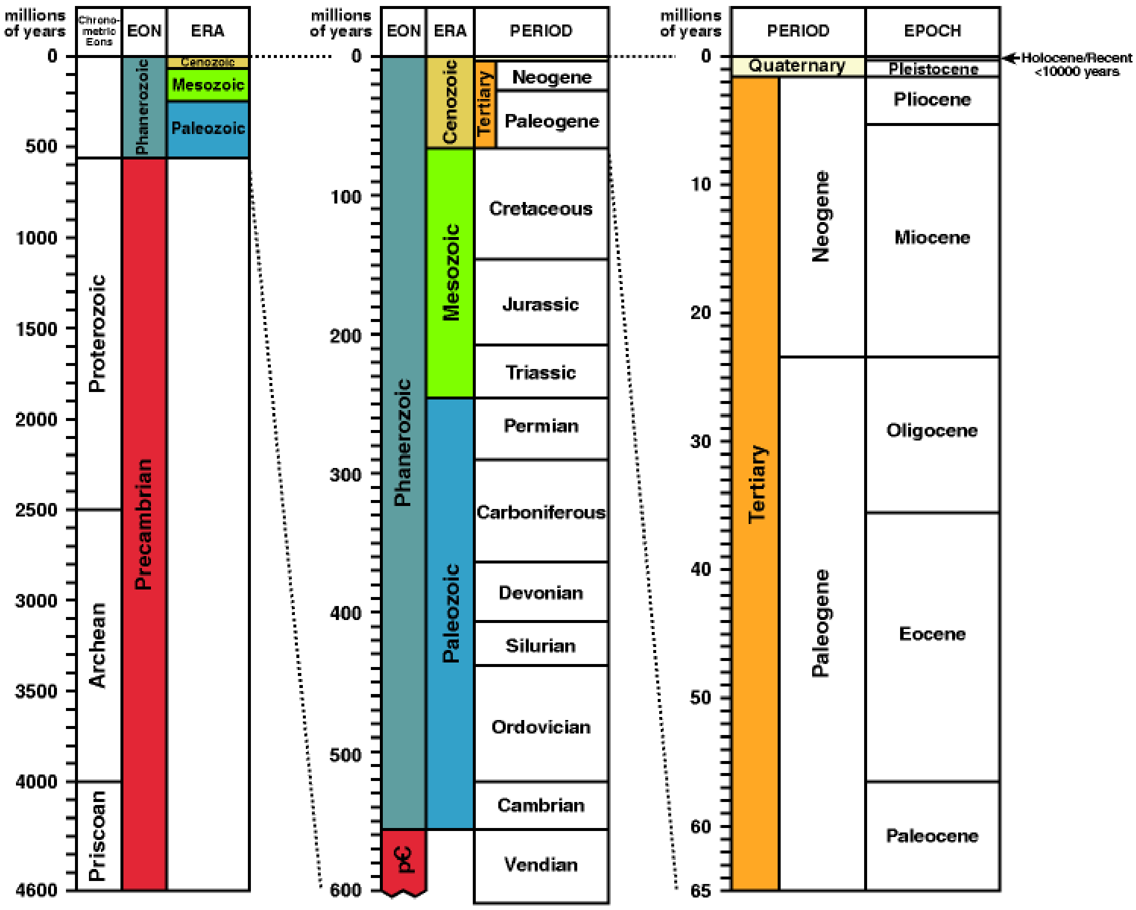


Figure 11: Geology time scale[iv]

The African continent (and Madagascar) comprises a mosaic of old, stable, mostly crystalline, crustal blocks (called cratons) surrounded, and welded together, by an interconnected network of younger orogenic belts comprising deformed metamorphic rocks and granites (called mobile belts; Figure 12). This jigsaw of rock units formed over a 3.7 billion year (Ga) period of continental crust growth through rift- and subduction-related magmatism, terrane accretion and continental collision during a series of supercontinental cycles. More specifically, the Kaapvaal, Zimbabwe, Tanzanian, Congo-Bangweulu and Antananarivo Cratons in the interior regions of sub-Saharan Africa represent ancient Archean cores enveloped by younger the Paleo- and Mesoproterozoic Ubendian, Kheis-Magondi, Namaqua-Natal, Mozambique, Sinclair and Irumide mobile belts which in turn are surrounded by yet younger Neoproterozoic 'Pan-African' West Congolian, Damara, Zambezi, East African and Saldanian orogenic belts (Figure 12).

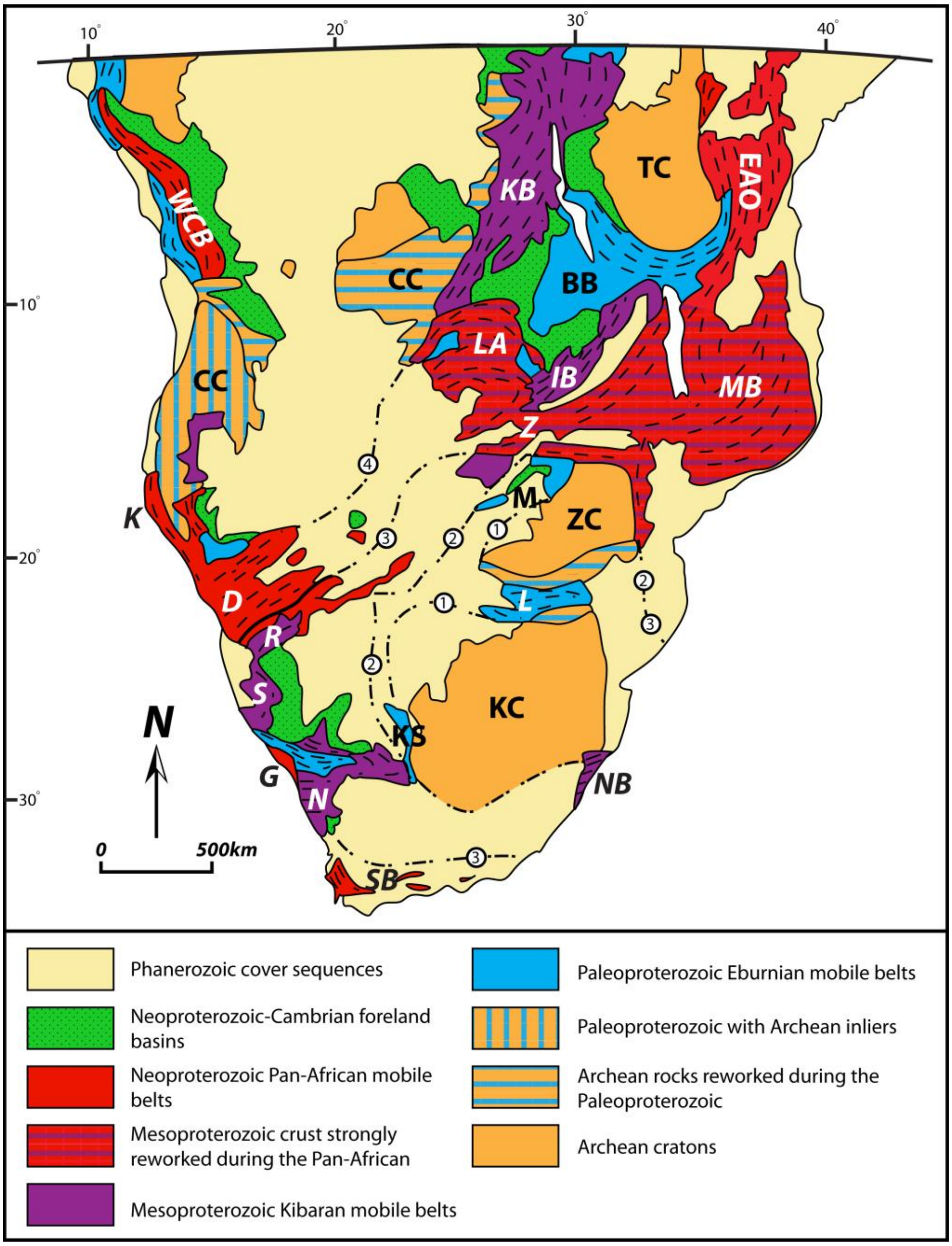


Figure 12: A regional tectonostratigraphic map of the SADC region showing the location of Archean cratonic regions surrounded by Proterozoic mobile belts and overlain by Phanerozoic cover sequences.
KC=Kaapvaal craton, ZC=Zimbabwe craton, TC=Tanzania craton, BB=Bangweulu Block, CC=components of Congo craton; R=Rehoboth Belt, L=Limpopo Belt, KS=Kheis Belt; M=Magondi Belt; S=Sinclair Belt, N=Namaqua Metamorphic Province, NB=Natal Province, IB=Irumide Belt, KB=Kibaran Belt, MB=Mozambique Belt, D=Damara Belt, K=Kaoko Belt, G=Gariep Belt; SB=Saldanian Belt, EAO=East African Orogen, LA=Lufilian Arc, Z=Zambezi Belt, WCB=West Congolian Belt. 1=extent of Kaapvaal and Zimbabwe cratons; 2=Extent of Kaapvaal-Limpopo-Zimbabwe craton; 3=Extent of Kalahari craton; 4= southern extent of Congo craton (diagram modified after Hanson, 2003).

The Pan-African belts fused the older cratons together during the amalgamation of the last supercontinent Gondwana forming a Precambrian basement to extensive Gondwanide sedimentary basins, most notably the Cape and Karoo Supergroups (Figure 13). The break-up of Gondwana in the mid- to Late Mesozoic was associated with extensive outpourings of lava and the intrusion of sills and dyke swarms throughout the Karoo Basin as well as the development of on- and off-shore sedimentary rift grabens.

Major warping of the southern African crust during the Cenozoic resulted in the formation of a large basin into which the Kalahari Group was deposited (Figure 13). The rifting of the African (into Nubian and Somalian plates) has seen the development of the East African Rift Valley and associated volcanic activity.

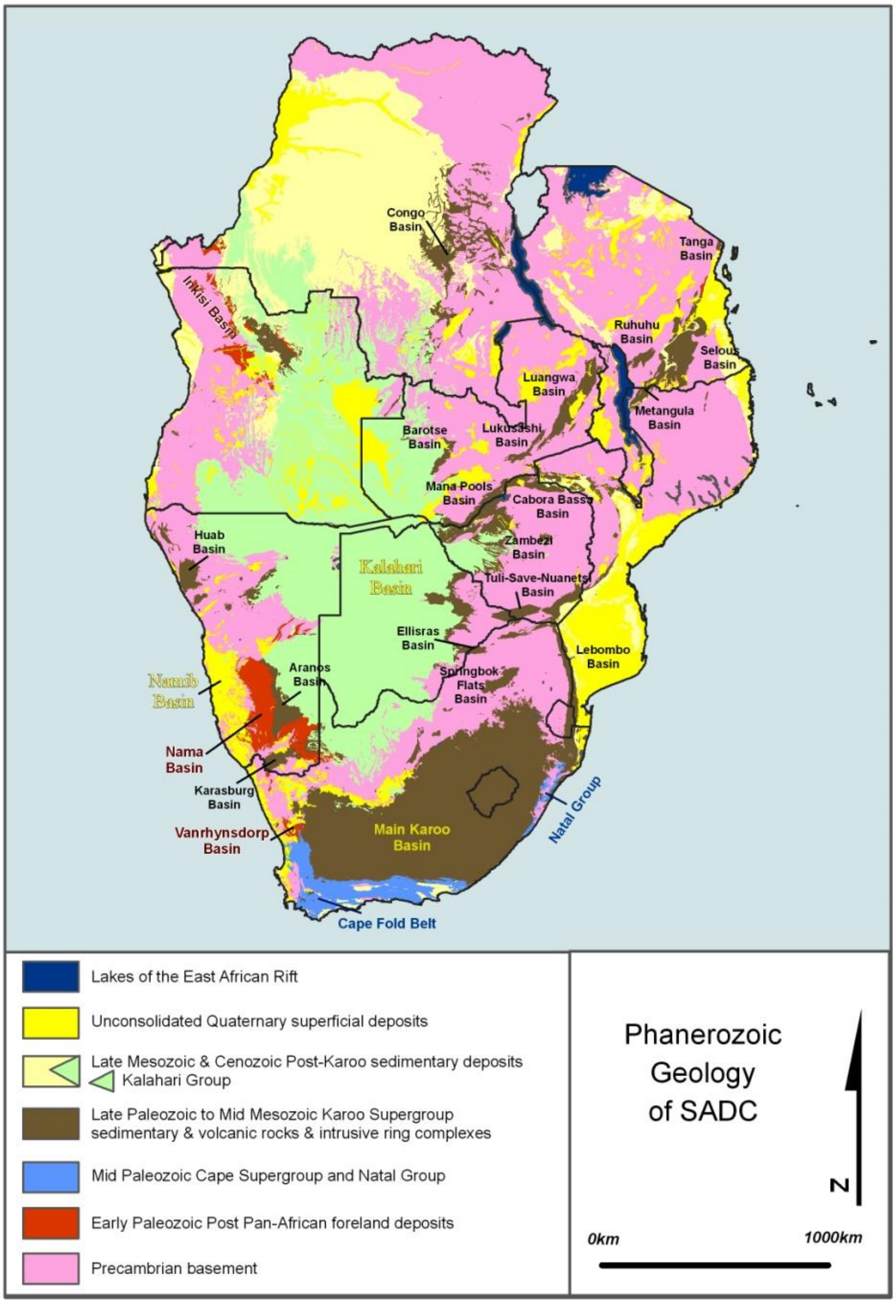


Figure 13: The Phanerozoic geology of the SADC region with the main sedimentary basins labeled. The Proterozoic mobile belts are shown in blue and the Archean cratons in pink. This map represents a simplification of the SADC geology map compiled by Hartzer (2008).

3.1.2. Precambrian Geology

3.1.2.1. Archean cratons

The cratonic regions of southern Africa (Kaapvaal, Zimbabwe, Congo and Tanzanian) developed between about 3.7 and 2.0Ga (Figure 12). The oldest parts of the cratons comprise small low grade Palaeoarchean meta-volcano-sedimentary greenstone belts that occur as isolated rafts in the vast intrusions of Paleo-Mesoarchean granitoid rocks dominated by tonalite-trondjemite-granodiorite (TTG) gneiss and granite.

Following stabilisation, the largely crystalline granitoid-greenstone micro-continents were buried by a series of sedimentary and volcanic sequences that accumulated in a number of basins from the Mesoarchean to the Paleoproterozoic (Figure 12). For example, the Kaapvaal craton was covered by supracrustal sequences of the Dominion and Pongola Groups (~3.07Ga), the Witwatersrand (~3.0-2.7Ga), Ventersdorp (~2.7Ga) and Transvaal (~2.6-2.1Ga) Supergroups and the Olifantshoek (~1.9Ga), Waterberg and Soutpansberg Groups (~1.8Ga). The sequences consist of a range of rock types including vast outcrops of dolomite, quartzite, conglomerate, ironstone and shale that form a veneer over the granitoid-greenstone basement. Whilst some of these supracrustal rock units were strongly tectonised and metamorphosed during subsequent orogenic episodes, the majority were protected by the rigid underlying craton and display only limited ductile deformation and low grade metamorphism. The sedimentary sequences were deposited in associated with, and are separated by, several major tectonic and magmatic events. Significant igneous events included the intrusion of the Great Zimbabwe Mafic Dyke (2.58Ga) and the Bushveld Igneous Complex (~2.05Ga) layered mafic intrusion, granites and felsic lavas). The ~80km wide Vredefort dome in central Kaapvaal preserves the devastating effects of a massive meteorite impact at 2.02Ga.

3.1.2.2. Proterozoic Mobile belts

The cratons and their Archean and Paleoproterozoic cover sequences are surrounded by a series of younger orogenic belts (Figure 12). The oldest of these is the Limpopo Belt, which developed as a result of the collision of the Kaapvaal and Zimbabwe cratons during the late Archean (~2.6Ga) and formed a 250km-wide zone of intensely deformed high grade metamorphic rocks (largely reworked older cratonic rocks) and granitoids. Tectonic activity was rejuvenated at about 2.0Ga resulting in a complex tectono-metamorphic history for the belt. The remainder of the mobile belts of the SADC region can be attributed to one of three major global Proterozoic supercontinental rift-drift-collision cycles known as the Eburnian (2.2 – 1.8 Ga), Kibaran (1.35–0.95 Ga), and Pan-African (0.8 – 0.5) episodes, related to the amalgamation and break-up of three supercontinents: Columbia, Rodinia and Gondwana, respectively.

3.1.2.2.1. Paleoproterozoic Eburnian Cycle: Columbia Supercontinent

The Eburnian of Southern Africa is represented by the Ubendian-Usagaran Belt, sandwiched between the Bangweulu Block (the Paleoproterozoic part of the Congo Craton) and the southern margin of Tanzanian Craton, and the Kheis-Okwa-Magondi Belt which developed when the Congo Craton collided with the Kaapvaal-Limpopo-Zimbabwe micro-continent at about 1.8Ga. The elongate 600km long, 150km wide Ubendian Belt comprises a number of lithotectonic terranes comprising high grade orthogneiss, migmatite, paragneiss and syn- to post-tectonic granitoids that were deformed together during the Eburnian Orogeny.

The collision along the Kheis-Okwa-Magondi Belt resulted in east-vergent folding and thrusting and low grade metamorphism of the older continental cover sequences that had been deposited along the margins of the Kaapvaal and Zimbabwe cratons. Further west, and now included as terranes of the Namaqua-Natal belt, arc granitoids and slivers of oceanic crust were accreted to the craton and granite magmas intruded the crust. Both the Ubendian-Usagaran and Kheis-Okwa-Magondi belts were at least partially, reworked by the subsequent Mesoproterozoic Orogeny.

3.1.2.2.2. *Mesoproterozoic Kibaran Cycle: Rodinia Supercontinent*

The Mesoproterozoic amalgamation of the Rodinia Supercontinent was responsible for the development of the next group of mobile belts, the Rehoboth-Sinclair, Namaqua-Natal, Mozambique, Irumide and Kibaran Belts (Figure 12). These mostly medium to high grade granite-gneiss belts formed mainly as a result of a combination of accretion of old micro-continents and exotic juvenile terranes, Paleo-to Mesoproterozoic sedimentation and several phases of deformation associated with syn- to post-orogenic granitoid magmatism. The amphibolite-grade Kibaran Belt forms a linear NE–SW oriented terrane of meta-sedimentary and meta-granitoid rocks that was sandwiched in between the Tanzania Craton/Bangweulu Block and the Congo Block. The intensely deformed rocks of the Irumide Belt comprise a melange of units including reworked rocks of the Archean cratonic margin, Paleoproterozoic orthogneiss complexes, Paleoproteozoic meta-sedimentary rocks and pre- and post-tectonic Mesoproterozoic granitoids. Metamorphic grades range from greenschist facies in the foreland to the northwest to upper amphibolite facies in the southeast, with local granulites.

The intensely deformed, medium to high grade metamorphic rocks of Sinclair-Namaqua-Natal and Mozambique Belts are dominated by orthogneisses and post-tectonic granites with paragneisses occurring as smaller discrete lenses within the tectonic melange. The continental lithosphere of the Kaapvaal-Limpopo-Zimbabwe-Kheis-Magondi-Namaqua-Natal micro-continent cratonised through cooling and thickening to form a new rigid crustal block referred to as the Kalahari Craton.

3.1.2.2.3. *Neoproterozoic Pan-African Cycle: Gondwana (Pangea) Supercontinent*

At around 750 million years ago, Rodinia began to split apart and rifts developed between, and along the margins of, the Congo and Kalahari Cratons into which coarse clastic sediments were deposited in association with limited bimodal rift volcanism. Continued extension over the next 100-200 million years (Ma) led to deepening basins and marine incursion accompanied by the deposition of generally more argillaceous sediments and carbonate rocks. Rifting eventually gave way to continental drifting and the formation of oceanic crust. Widespread glacial till deposits and overlying cap carbonate rocks observed within most of the Pan-African sedimentary successions indicate this period was a time of extreme global climate fluctuations.

Tectonic inversion of the rift structures and closure of the oceanic basins toward the end of the Proterozoic culminated with the collision of the older cratonic fragments and the intense deformation of the interleaving Pan-African volcano-sedimentary successions to form Gondwana (Figure 14). The medium temperature, medium to high pressure Zambezi-Lufilian-Damara Belt developed across central and western SADC during the collision of the Congo and Kalahari cratons, whereas the predominantly low grade Gariep, Kaoko and West Congolian Belts of the African west coast formed when the Kalahari-Congo collided with the Rio de la Plata-Sao Francisco of South America (Figure 14). In the East African Orogen of Mozambique and Madagascar, Pan-African sedimentary deposits are limited and the orogen is characterised by strongly reworked older rock units. All of the Pan-African belts were intruded by moderate to large volumes of late- to post-tectonic granites in the final stages of the supercontinent amalgamation.

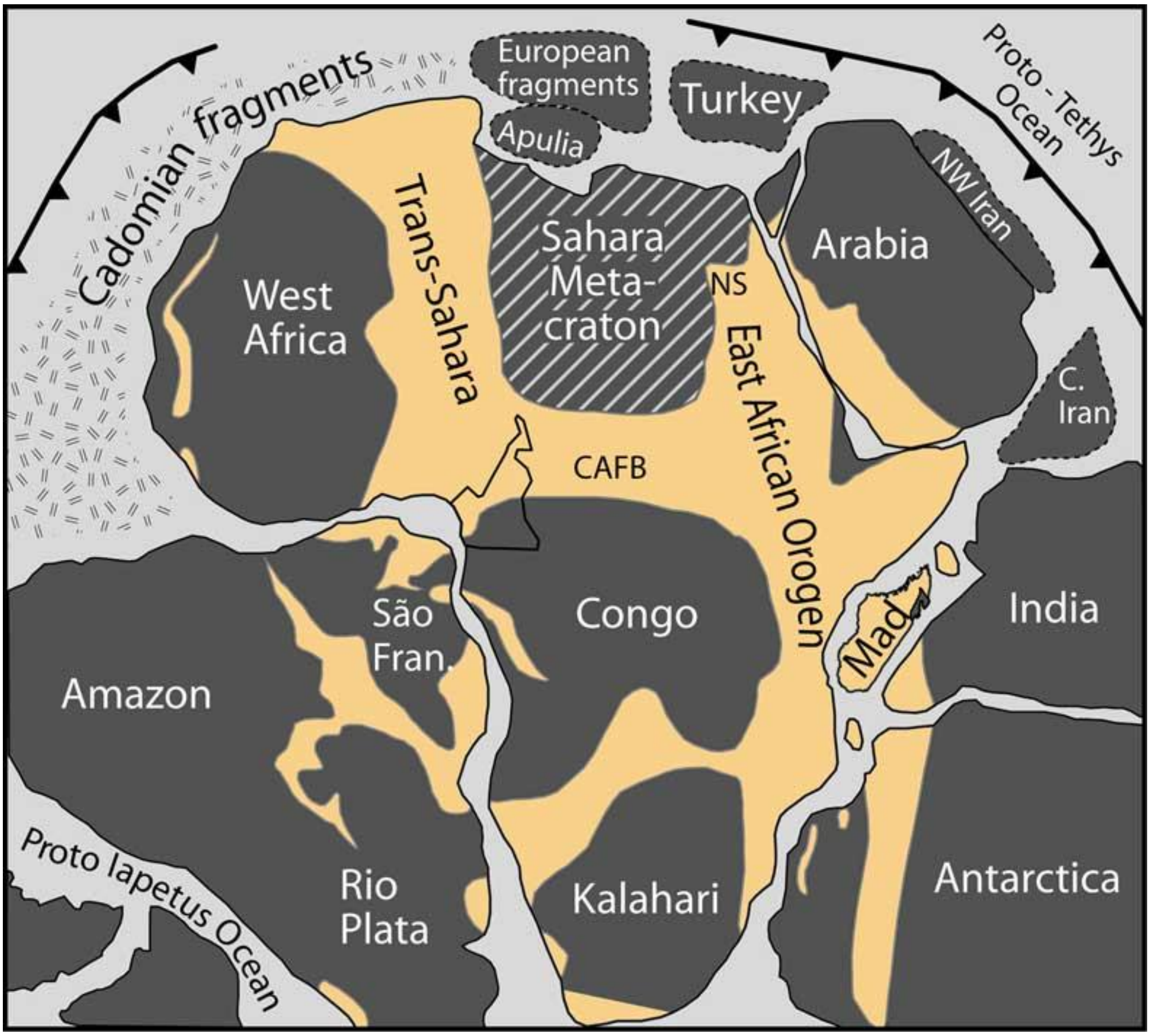


Figure 14: A plate reconstruction of the Supercontinent Gondwana

The Pan-African mountain building and associated lithospheric flexure towards the end of the Gondwana assembly resulted in the formation of foreland basins inboard and peripheral to the newly formed mobile belts into which Cambrian clastic-carbonate sequences were deposited . In south western Africa the Nama (1000km long; <700m thick) and Vanrhynsdorp Groups (~2300m thick) were deposited along the SW edge of the Kalahari craton. Similar deposits (Inkisi Formation) are located along the western Congo Craton edge, inboard of the West Congolian Belt of the DRC and Angola. The shale-siltstone-sandstone-limestone sequences were deposited in the waning stage of the Pan African Orogeny and hence preserve evidence of only limited fold-and-thrust deformation and low grade metamorphism.

3.1.3. Paleozoic-Mesozoic Geology

The SADC region during the first 300 million years of the Phanerozoic Era was located mostly within and along the southern margin of Gondwana (Figure 14) and it's geological history during this period was characterised mainly by deposition of a series of thick sedimentary successions unconformably onto the Precambrian-Cambrian basement rocks of the supercontinent (Figure 13).

3.1.3.1. Early Paleozoic Cape Supergroup and the Permo-Triassic Cape Orogeny

The Cape Basin developed along the southern margin of Gondwana into which a southward thickening wedge, reaching more than 8km thick, of Ordovician to Early Carboniferous (~500-330Ma) passive continental margin sediments accumulated. The clastic shallow marine, deltaic and near shore fluvial sandstones, shales and minor conglomerates of the Cape Supergroup extend for more than a 1000km across the southern and western Cape of South Africa, deposited largely upon the rocks of the Pan-African Saldania Belt .

The Cape Supergroup, and the lower units of the overlying Karoo Supergroup, succession were deformed during the Permian-Triassic Cape Orogeny. The most favoured model for the development of the low grade fold-and-thrust Cape Fold Belt (and the adjacent Karoo Basin) is the collision of micro-continents along an arc-subduction zone positioned along the southern margin of the Cape Basin.

3.1.3.2. Late Paleozoic-Mesozoic Karoo Supergroup

The Late Carboniferous to Jurassic sediments of the Karoo Supergroup (with a cumulative thickness of 12km) were deposited in numerous basins across large tracts of Gondwana, many of which, including the main Karoo Basin, are found in sub-Saharan Africa. The main Karoo sedimentary basin is considered to represent a retro-arc foreland basin that developed through flexural tectonics in response to the same continental collisions along the southern margin of Gondwana responsible for the Cape Fold Belt. In contrast, the northern basins are considered transtensional rifts that propagated southwards from the opposite margin of Gondwana.

In the main Karoo basin, glacial diamictites of the Late Carboniferous to Early Permian Dwyka Group form the lowermost parts of the succession, unconformably overlying either Precambrian basement or the Cape Supergroup. The main Karoo Basin developed into a deeping inland sea during the Permian into which the mostly argillaceous marine sediments of the Ecca Group accumulated. The Triassic saw the basin environment change from marine to terrigenous, with fluvial sandstone and mudrock deposits the dominant components of the Beaufort Group and Molteno and Elliot Formations. The period was associated with progressively increased arid conditions across the region evidence of which is preserved in the aeolian deposits of the Late Triassic-Early Jurassic Clarens Formation. Lithostratigraphic studies in the Karoo-aged basins north of the main Karoo Basin permit substantial stratigraphic correlation between the various basins and the main Karoo Basin. The correlations are not universal, however, and local tectonic controls and climatic differences have resulted in significant differences in the lithological character, thicknesses, and relative preservation of the various sequences.

3.1.3.3. Mid-Late Mesozoic break-up of Gondwana

The piecemeal break-up of Gondwana began by about 180 million years ago in response to a mantle plume. In the SADC region the rifting of the Africa-South America block (West Gondwana) from the India-Antarctica-Australia-Madagascar block (East Gondwana) was accompanied by massive outpouring of Drakensberg flood basalts fed by basaltic dykes and sills, and forming the resistant cap rock of the Karoo Supergroup. Today, the basaltic lavas occur as erosional remnants and dominating the mountain kingdom of Lesotho. The subsequent split of Africa from South America occurred in the Cretaceous at about 135Ma and was also associated with volcanic activity as well as the intrusion of a string of spherical igneous ring complexes best observed in northern Namibia. Similarly, in the Late Cretaceous (~90Ma) extensive volcanic deposits and associated intrusive dyke swarms and ring complexes developed across Madagascar as the island finally broke free of India.

The regional extension related to Gondwana break-up was also responsible for the formation of isolated, relatively small, rift grabens along the southern continental crust of South Africa into which coarse clastic sedimentary rocks were deposited.

3.1.4. Cenozoic geology

3.1.4.1. Inland Cenozoic Basins

In the interior of sub-Saharan Africa, the greater Kalahari Basin extends from northern

South Africa to equatorial Gabon (Thomas and Shaw, 1991). The older units occur mainly in the south (South Africa, Botswana and Namibia), but the younger, mainly aeolian sands have a much wider distribution and constitute the largest palaeo-desert in the world. The thickest sediments, ranging up to 210 m, are confined to palaeo-valleys frequently associated with the Palaeozoic Dwyka Group and may thus be influenced by ancient glacial valleys. Late Cretaceous drainages, faulting associated with the East African Rift as well as meteorite impact craters also influenced sediment isopachs of the Kalahari Group (Partridge et al., 2006). The basal Wessel Formation comprises a clayey gravel of probable Miocene fluvial origin. The overlying Budin Formation comprises brown and reddish calcareous clays possibly representing lacustrine sedimentation and has a wider distribution than the Wessel Formation. The succeeding Eden Formation consists of yellow-red and brown sandstones and thin gravels most likely deposited by braided streams, overlain by the calcretes of the Mokalanen Formation, which possibly straddles the Plio-Pleistocene boundary and heralds the onset of (periodic) extreme Kalahari aridity. The most extensive unit is the Gordonia Formation, mainly comprising fossilised linear dunes which are active only in the south. Although a geographically separate unit chiefly confined to southwestern Namibia, the Namib Sand Sea corresponds with the younger, chiefly aeolian units of the Kalahari Basin, but also contains older (Miocene-Pliocene) elements referred to as the Tsondab Sandstone Formation (Senut and Pickford, 1995). The Congo Basin is essentially contiguous with the greater Kalahari Basin and contains terrestrial Palaeogene, Neogene and Quaternary sediments (Giresse, 2005).

3.1.4.2. Coastal Cenozoic deposits

Cenozoic deposits of littoral marine, estuarine, fluvial, lacustrine and aeolian origin are developed extensively along the coastal plains of sub-Saharan Africa (Selley and Ala, 1997; Roberts et al., 2006). In general, these deposits are thin due to the buoyancy of these passive coastlines over the past 60 million years and consist mainly of Neogene to Quaternary sediments. However, in the vicinity of major river mouth such as the Congo and Zambezi, thick sediment cones and deposits in extensional rift basins have accumulated on- and offshore (Dingle et al., 1983). These strata are economically important, containing reserves of hydrocarbons, diamonds, heavy minerals, phosphate and groundwater. In general, the western basins comprise pre-rift Mesozoic terrestrial clastic sediments near the base, overlain by Cretaceous evaporites and marine clastics. These strata are succeeded by Palaeogene, Neogene and Quaternary deposits, notable for the absence of Oligocene representatives (Selley and Ala, 1997). The chief counterpart of these basins on the east African coast is the Lebombo/ Mocambique Basin extending from South Africa into Mocambique. This basin comprises thick deltaic deposits of several major rivers ranging in age from Mesozoic to Quaternary. The Lindi Rift Basin situated in southeast Tanzania contains Palaeogene marine sediments, faulted during the Miocene development of the rift system. (Mbede and Dualeh, 1997).

3.1.4.3. East African Rift

Whilst much of the SADC region has been largely tectonically stable since the break-up of Gondwana, the East African Rift Valley represents the locus of the relatively recent splitting of the African Plate into the Nubian and Somalian subplates. Rifting, and associated volcanism, began at the southern end of the Red Sea about 20 million years ago and has progressively extended southwards forming the wide graben and the great lakes such as Victoria and Malawi-Niassa of Tanzania and Malawi. The most southerly branches of the rift extend to, and affect the drainage basins of, the Okavango Delta in the west, and into central Mozambique in the east.

Mauritius is a volcanic island. It consists essentially of a mass of volcanic debris thrown up from craters now extinct. "Forming part of the Réunion hotspot trace, the island of Mauritius (along with Réunion Island and Rodrigues ridge) rose from the Indian ocean floor as a basalt volcano about 8 million years ago."

3.2. Geomorphology

The present landscape of southern Africa is the end-product of geomorphic processes acting on rocks of variety types and ages. The macro-scale geomorphic development of the subcontinent is a result of periods of tectonic uplift, which have induced erosion, the stripping of the Karoo rocks and the superimposition of drainage patterns. A number of erosion surfaces have been identified. The oldest surface, which is the most widespread, is termed the African surface. The surface below the African in the interior has been named the Post-African. Seaward of the Great escarpment, however two surfaces of Post-African age have developed and these are referred to as the Post-African I and Post-African II. These erosion surfaces play an important part in basement aquifer development. The deeper weathering profiles associated with the oldest erosion surfaces.

The Kalahari basin formed as a result of subsidence of the interior during the Late Cretaceous. Rivers were back-tilted into Kalahari basin resulting in the deposition of the Kalahari sediments. Uplift in the Pliocene resulted in erosion of Karoo rocks and basal Kalahari sediments resulting in reworking and deposition of the eroded sand. This reflects the extensive dune fields that are preserved today (Figure 15).

The Congo basin is contained within the Congo craton. The Congo Basin developed and evolved as a result of rifting and subsequent drifting of the African continent from South America. Sediment infill has occurred from the late Proterozoic to Quaternary.

Figure 15: Kalahari sand dune[v]

3.3. Climate

The rainfall map is given in Figure 16. The amount of rainfall varies tremendously throughout the SADC region with desert areas and tropical forests. Average annual rainfall varies from more than 1 400 mm in the north to less than 50 mm in south-western parts of the region. The lower rainfall in the south and southwest regions of SADC means that many of the rivers are ephemeral.

Drought is a common occurrence in SADC. The 1991-1992 droughts were the worst of the century. There were seasonal deficits of as much as 80% of normal rainfall throughout SADC. Abnormally high temperatures (47°C along the South Africa-Zimbabwe border) exacerbated the extreme dryness.

The 1991-92 droughts caused the Zimbabwe stock market to decline by 62 per cent, causing the International Finance Corporation to describe the country as the worst performer out of 54 world stock markets (UNEP 2002).

The 2000/2001 flood events that affected Mozambique resulted in heavy losses (Figure 17). This was due to abnormal rain throughout southern Africa. The region has also been hit by cyclones. Cyclone Ivan struck Madagascar on Sunday 17 February 2008 and made its trail across the country, causing severe damage. 28 people died as a result.

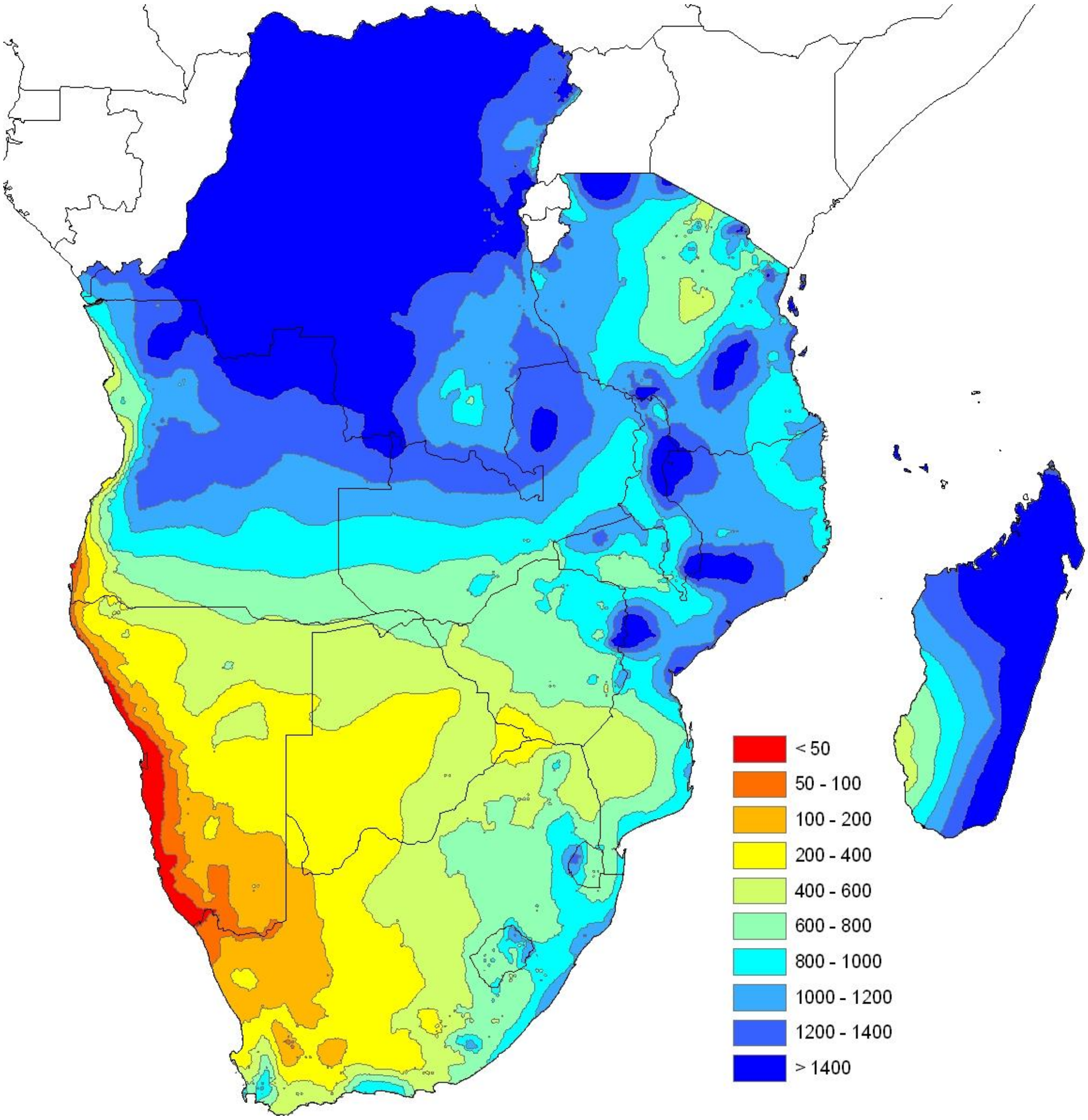
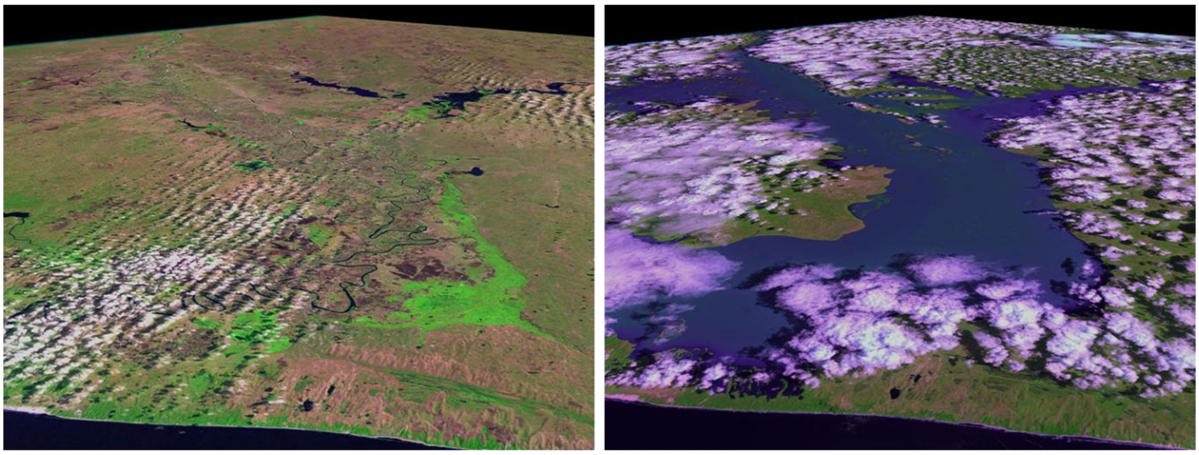


Figure 16: Mean Annual Rainfall in the SADC region (1961 – 1990)((New, et al. 2002).



(a) (b)

Figure 17: Flooding in 2000 (a) Mozambique in August 1999 (b) During the flooding in March 2000 (NASA/USGS)

3.4. Surface hydrology

The Southern African Development Community (SADC) has fifteen international shared rivers Figure 18. It is estimated that more than 70 per cent of the region's surface water resources are shared between countries.

The Congo River basin is the largest and the Congo is also the longest river in SADC. This is followed by the Zambezi River, which extends to eight Member States (Figure 19). The runoff estimates for all the river basins in SADC are given in the Table 1.

The region also has a number of large lakes:

- Lake Victoria
- Lake Tanganyika
- Lake Malawi/Nyassa

The basis for sharing these resources between countries is the Protocol on Shared Watercourse Systems. The protocol calls on Member States to:

- Develop close co-operation for judicious and coordinated utilization of the resources of shared watercourses
- Co-ordinate environmentally sound development of shared watercourses in order to support socio-economic development.
- Exchange information and consult each other

Future projections suggest that average water availability per person will sharply decline for most SADC countries. Natural phenomena, climate variability, climate change and human factors, such as population growth, competition over water and water pollution, increasingly threaten the sustainability of water resources in SADC.

Transboundary water resource issues and challenges of Southern Africa are mostly related to regional integration and development and those specifically related to water resources planning and management, water related infrastructure, water governance, and capacity building and these call for cooperation amongst the countries in Integrated Water Resources Management (IWRM) and Development, especially along shared watercourses to ensure benefits for all. These protocols, although valid for groundwater, has not been implemented at aquifer transboundary scale.

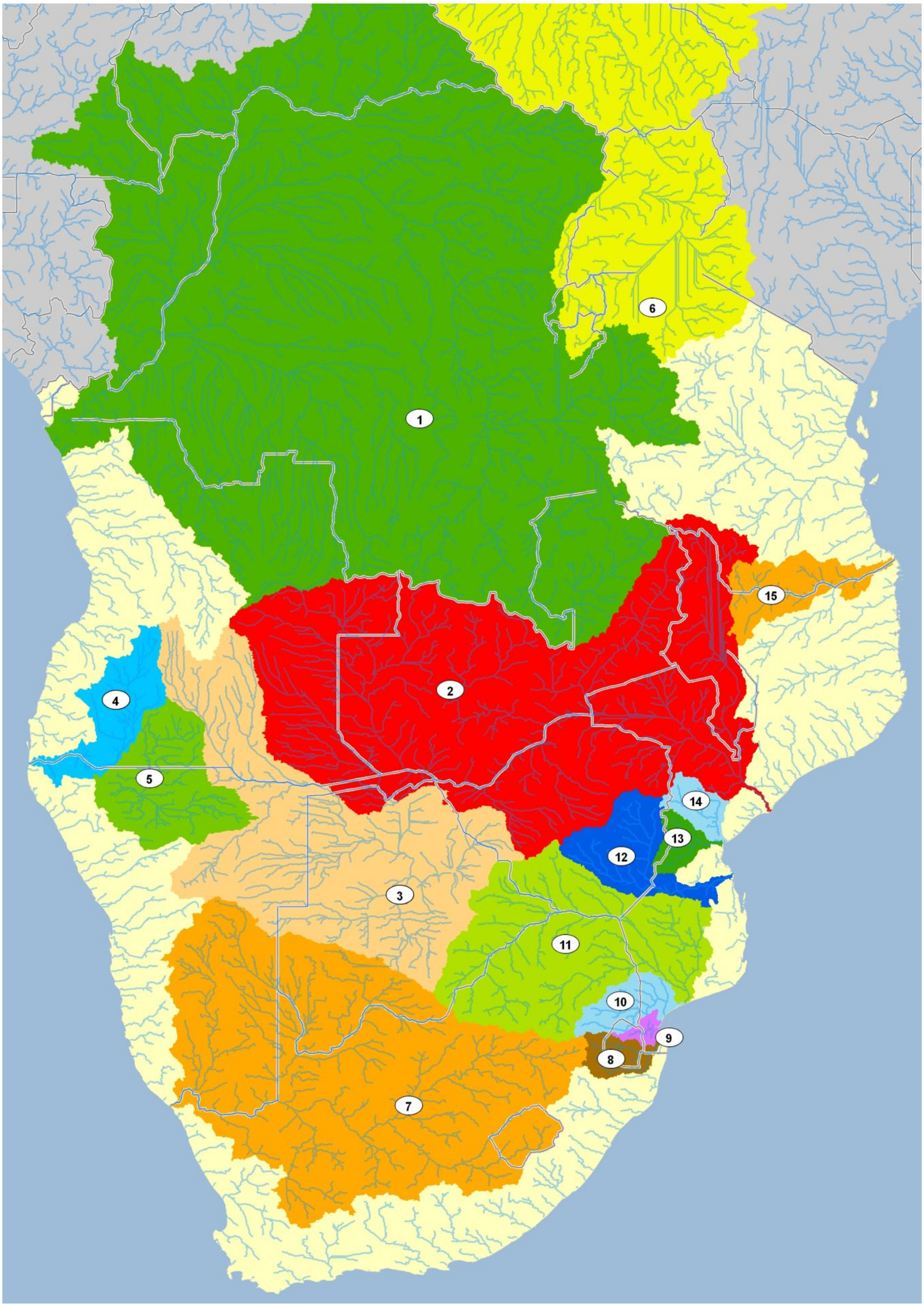


Figure 18: SADC river basins.
(1. Congo, 2. Zambezi, 3. Okavango/Cubango, 4. Cunene, 5. Etosha – Cuvelai, 6. Nile, 7. Orange River, 8. Maputo, 9. Umbeluzi, 10. Incomati, 11. Limpopo, 12. Save, 13. Buzi, 14. Pungwe, and 15. Ruvuma)

Figure 19: Pungwe river in flood *(Photograph courtesy of Rikard Lidén)*

Table 1: Statistics on the major international river basins in SADC.

River Basin	Basin Area (km^2)	Mean Annual Runoff at the River mouth (MCM/yr)	River Length (km)	No. of SADC states
Congo	2 942 700	1 260 000	4700	4
Zambezi	1 388 200	94 000	2650	8
Orange	947 700	11 500	2300	4
Okavango/Cubango	708 600	11 000	110	4
Limpopo	415 500	5 500	1750	4
Etosha-Cuvelai	167 600	n.a	430	2
Ruvuma	152 200	15 000	800	3
Nile	142 000	68 000	6700	2
Sabi/Save	116 100	7 000	740	2
Cunene	110 300	5 000	1050	2
Incomati	46 200	3 500	480	3
Pungwe	32 500	3 000	300	2
Maputo	31 300	2 500	380	3
Buzi	27.900	2.500	250	2
Umbeluzi	5.400	600	200	3

4. The Hydrogeological map

"We, as hydrogeologists, are at present in a unique position to both meet what will be the most urgent societal needs of the next century and to advance scientific understanding of the earth system, but we will only be able to accomplish this if we stretch our vision beyond the limits we ourselves have defined for our field"

Fred M Philips, 2005

4.1. Coverage

The interactive web-based hydrogeological map (Figure 20) and atlas was produced at a scale of 1:2.500 000 (at the same scale as the SADC geological map). The map comprises the following layers:

- Roads, capitals and major towns
- International boundaries
- Mines
- Digital elevation model
- Rainfall
- Recharge
- Surface water features, including perennial and non-perennial rivers
- International river basins
- Lithology and geological structures
- Aquifer types and associated groundwater productivity
- Transboundary aquifers
- Water quality

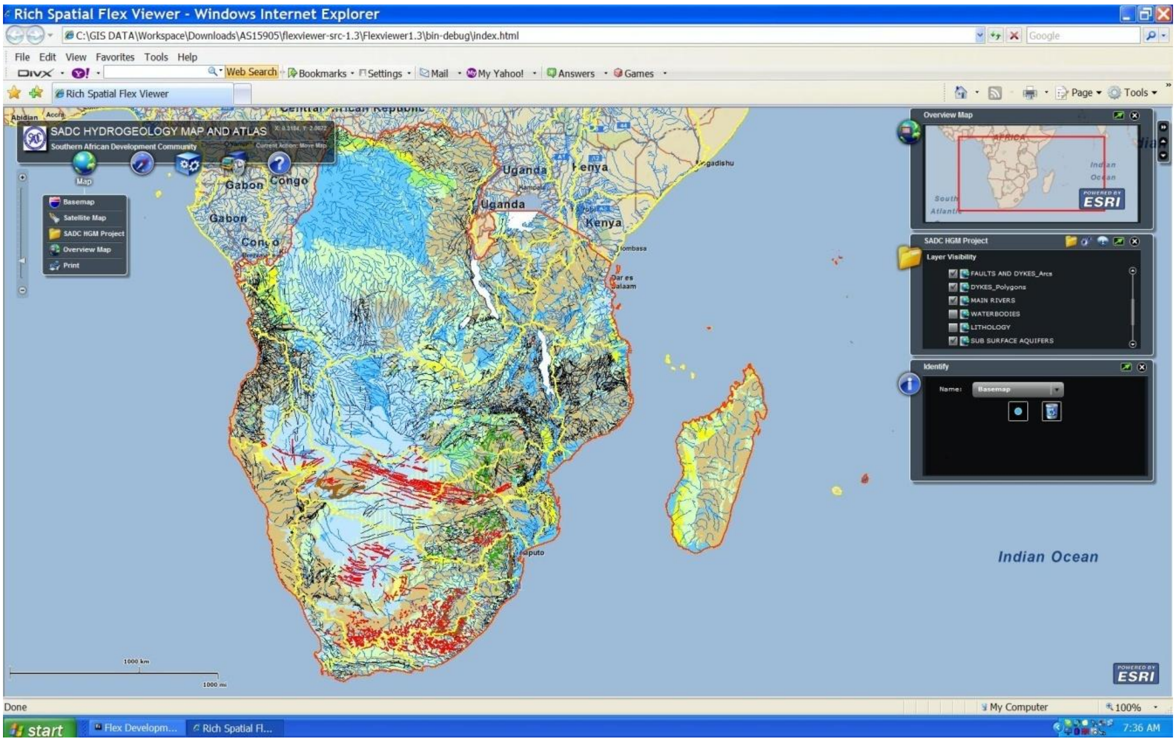


Figure 20: Screenshot of the SADC hydrogeological map web interface

4.2. Legend

A legend for the SADC HGM and atlas has been prepared. The legend and associated symbol sets have been developed for display in a web interface. The International Association Hydrogeologists (IAH) standard legend for groundwater and rocks was adopted to compile the hydrogeological map, the only difference being the separation of fissured and karst aquifers. This was done because karst rocks form important high yielding regional aquifers that are prone to over-exploitation and vulnerable to pollution. The symbol sets for the map layers are presented in Figure 21.

Figure 21: Symbol sets for the SADC HGM Legend

4.3. Compiling the hydrogeological map

4.3.1. Groundwater information system

A major outcome was the completion of the SADC Hydrogeologic Mapping Borehole Database (Figure 22). The database was designed to support the hydrogeological mapping process and contains the data that was submitted by Member States. The database holds approximately 335 000 records. The database has the following fields:

- Coordinates
- Borehole identity (id) or code
- Borehole depth
- Date of borehole completion
- Latest static water level (metres below surface), date of measurement
- Latest yield (litres/second)
- Latest electrical conductivity (mS/m)
- Latest fluoride (mg/L)
- Latest nitrate as NO_3 (mg/L)

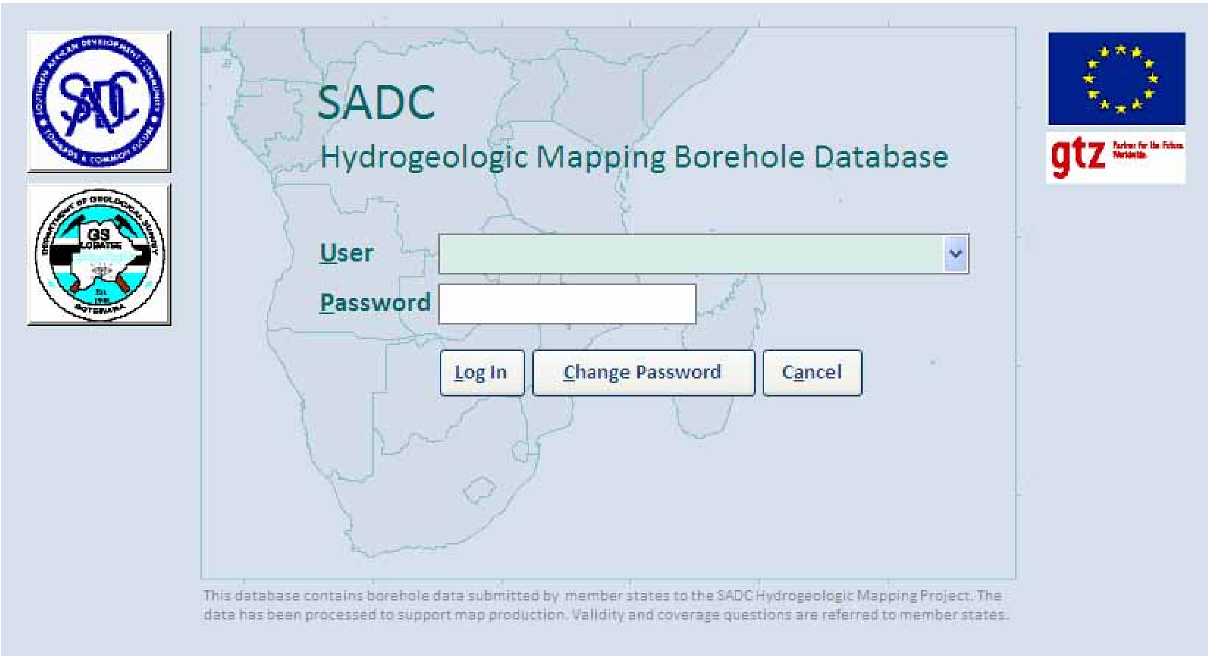


Figure 22: SADC Hydrogeologic mapping borehole database.

The database has search, filter, export and statistics functions. The database outputs can also be displayed in Google Earth and ArcGIS. The database also serves as a catalogue or portal and holds non-structured documents such as spreadsheets and word files. The custodian of the database is the Department of Geological Survey of Botswana.

4.3.2. Hydro -lithology base map

The hydro-lithology base map was compiled from the SADC geology map prepared by the South African Council for Geoscience (Hartzer, 2009). This was done through linking the stratigraphy to the rock types. The geology map has been simplified to 12 hydro - lithological classes (Table 2).

The SADC geology map formed part of a SADC project on geology, under the auspices of the SADC Mining Committee and the Geology Subcommittee. It formed part of a series of projects launched by this subcommittee in an effort to strengthen the mining industry in Southern Africa by enhancing and geological infra-structure. The map is the cumulative product from several years of work during which all the various SADC countries made contributions.

The SADC geology map is based on lithostratigraphic principals with lithology being the basis of the classification, using the specific stratigraphic name allocated to each unit. The original geology map contains about 730 different lithological units. For the purpose of the SADC hydrogeological map all these units or lithological classes were firstly grouped together into 29 different lithological classes, which was partially chosen for their hydrogeological features. For example silisiclastic sedimentary rocks such as sandstone and gravel were grouped in a separate class to chemical sedimentary rocks such as limestone. By its very nature silisiclastic sedimentary rocks would display a different hydrological character in terms of features such as porosity, than limestone. In the same manner distinction was made between sands and clays and very coarse sedimentary rocks such as tillites and diamictites. Volcanic rocks were separated from intrusive rocks. Furthermore a chronological distinction was also made separating older metamorphosed units from younger and less deformed and metamorphosed units.

After consultation with the various SADC countries it was decided to simplify these classes even further into 12 hydro-lithological units (Figure 23). The final classification retains the basic principles of the previous classification but has consolidated hydro-lithologies more. Even though this has meant that the chronological element in the classification has largely been done away with there is still an element of it in the sense that the granites and gneisses are obviously the older units and the unconsolidated sands and gravels are the youngest units. In the same sense a distinction is still being made between intrusive units such as granites and orthogneisses, and metamorphosed sedimentary units such as paragneisses.

Table 2: Hydro - lithological classes of the SADC hydrogeological map

Hydro - lithological classes
Unconsolidated sands and gravel
Clay, clayey loam, mud, silt, marl
Unconsolidated to consolidated sand, gravel, arenites, locally calcrete, bioclastites
Sandstone
Shale, mudstone and siltstone
Interlayered shales and sandstone
Tillite and diamictite
Dolomite and limestone
Volcanic rocks, extrusive
Intrusive dykes and sills
Paragneiss, quartzite, schist, phyllite, amphibolite
Granite, syenite, gabbro, , gneiss and migmatites

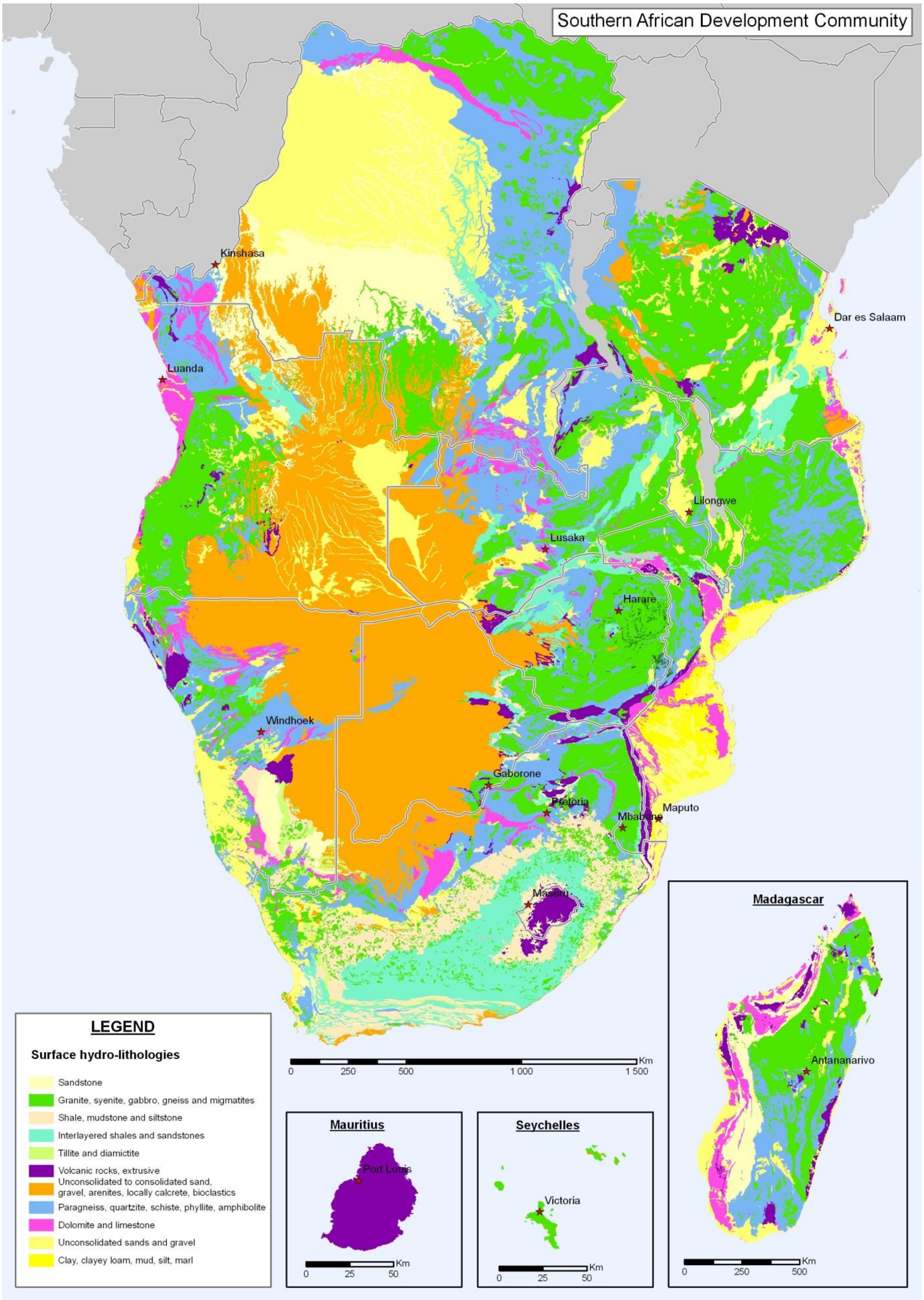


Figure 23: Hydro-lithology map of SADC.

4.3.3. Aquifer types

The main rock types have been grouped into permeable and low permeability formations using the lithology base map and expert judgement. Permeable formations have been further grouped into porous (gravel, alluvium, sand etc), fissured (sandstone, basalt, etc) and karst (limestone, dolomite, gypsum, etc). The following aquifer types have been depicted based on the groundwater flow regime.

- Unconsolidated intergranular aquifers
- Fissured aquifers
- Karst aquifers
- Layered aquifers
- Low permeability formations

4.3.3.1. Unconsolidated/intergranular aquifers

In unconsolidated or intergranular aquifers, groundwater is produced from pore spaces between particles of gravel, sand, and silt. An example is the Mushawe alluvial aquifer in the Limpopo Basin, Zimbabwe or the extensive shallow aquifer of the quaternary alluvial plain in DRC, which formed as a result of deposition of unconsolidated material in river channels, banks and flood plains. These aquifers are often closely associated with surface water flows and can maintain river flow during low flow conditions, especially during the dry season. During the rainy season, the opposite take place, the rivers normally recharge these alluvial aquifers. Perennial rivers also recharge the alluvial aquifers which are in contact with the water table. Alluvial aquifers are important water resources in SADC (Figure 24).

Figure 24: Large-diameter collector well upstream of a subsurface dam within the riverbed of a headwater tributary of the Limpopo River, Botswana[vi]

A number of major cities are located on the coast in SADC. These include Luanda, Cape Town, Port Elizabeth, Durban, Maputo, Beira, Dondo and Dar es Salaam. Some of these cities, to some extent, rely on unconsolidated coastal aquifers for various uses. Coastal aquifers have a hydraulic connection with the sea and are prone to the intrusion of sea water. These aquifers are also susceptible to pollution.

Groundwater is also abstracted from the Kalahari aquifers. The Kalahari Group consists of undifferentiated inland deposits of unconsolidated to semi-consolidated sediments including sands, calcrete, aeolianite, gravel, clay and silcrete. The Kalahari aquifer system extends across parts of DR Congo, Angola, Namibia, Zambia, Botswana and South Africa. For example, groundwater in the Cuvelai-Etosha Basin is found in a complex system of stratified aquifers containing fresh and/or saline water (BGR 2009). The saline water sometimes exceeds the salinity of sea water. No consistent system regarding the spatial distribution of fresh and saline water has yet been established, and the distribution of the depths and potential yields of the different layers is not yet known (BGR 2009)

4.3.3.2. Fissured aquifers

Rocks that are highly fractured have the potential to make good aquifers via fissure flow. This is provided the rock has an appreciable hydraulic conductivity to facilitate movement of water.

Aquifer systems associated with Karoo formations are found extensively throughout the SADC-region. The formations normally have low permeability and are low-yielding. However, where the rocks have been subjected to deformation and intrusion of dolerites a secondary permeability resulting in good aquifers may be found (Figure 25). In Botswana, the Karoo aquifers are the most productive and most exploited geological unit. The aquifers are sandstone aquifers and are normally overlain by Kalahari sediments. The same situation exists in Namibia.

The Cape Fold Mountains of South Africa are also associated with fractured rock aquifers. Groundwater occurrence is dependent on tectonic and structural controls resulting in higher hydraulic conductivities and transmissivities.

Figure 25: Karoo fractured aquifer: fractured dolerite dyke intruding mudstone / sandstone succession in the Karoo Basin (Near Victoria West, South Africa). The fissured aquifer occur at the contact sediment – dolerite where transmissivity is high (Photograph courtesy of Luc Chevallier).

4.3.3.3. Karst aquifers

Karst aquifers are water-bearing, soluble rock layers in which groundwater flow is concentrated along secondarily enlarged fractures, fissures, conduits, and other interconnected openings. They are formed by the chemical dissolving action of slightly acidic water on highly soluble rocks, most notably limestone and dolomite. Extensive use is made of karst aquifers in Namibia, Zimbabwe, South Africa and Botswana. In South Africa the dolomite aquifers give rise to some of the highest yielding boreholes in the country (up to 100 L/s). The naturally discharging spring of the Steenkoppies compartment near Johannesburg (known as "Maloney's Eye") had a mean annual discharge from 1908 to the late 1980's of 14 million m^3/annum, but average discharge has dropped to about 9.8 million m^3/annum in the last decade (Figure 26).

Figure 26: Maloney's Eye, a spring emanating from a Karst aquifer (*Photograph courtesy of Martin Holland)*

4.3.3.4. Low permeability formations

Low permeability formations are normally associated with basement aquifers (Figure 27). The poor connectivity of bedrock fractures and heterogeneity result in significant local variations in yield and response to abstraction. These formations occur extensively throughout the SADC-region. In southern Africa, basement aquifers constitute approximately 55 per cent of the land area.

Basement aquifers are composite aquifers, comprising a variable thickness of weathered overburden overlying bedrock, the upper part of which is frequently fractured. The weathered overburden is usually the main groundwater storage compartment although boreholes may be developed in the underlying fractured bedrock.

Due to the inherent small storage capacity of basement aquifers, favourable recharge conditions are crucial if they are to be viable sources of water supply

Figure 27: Typical appearance of basement aquifers that are characterised by hydraulic conductors (fractures and fissures) that developed in Precambrian basement lithologies (*Photograph courtesy of Paul Macey*)

4.3.3.5. Layered aquifers

The SADC geology map is a surface lithology map. In a number of cases aquifers are found at depth and are overlain by cover material and are therefore not depicted. The Kalahari/Karoo aquifer system shared between Botswana, Namibia and South Africa is an example. In the so-called "Stampriet Artesian Basin" there are two confined regional artesian aquifers in the Karoo sediments, overlain by the Kalahari sediments that often contain an unconfined aquifer system (Figure 28). Thus, water occurs in the Auob and Nossob sandstones of the Ecca Group (lower Karoo Sequence), as well as in the overlying Kalahari.

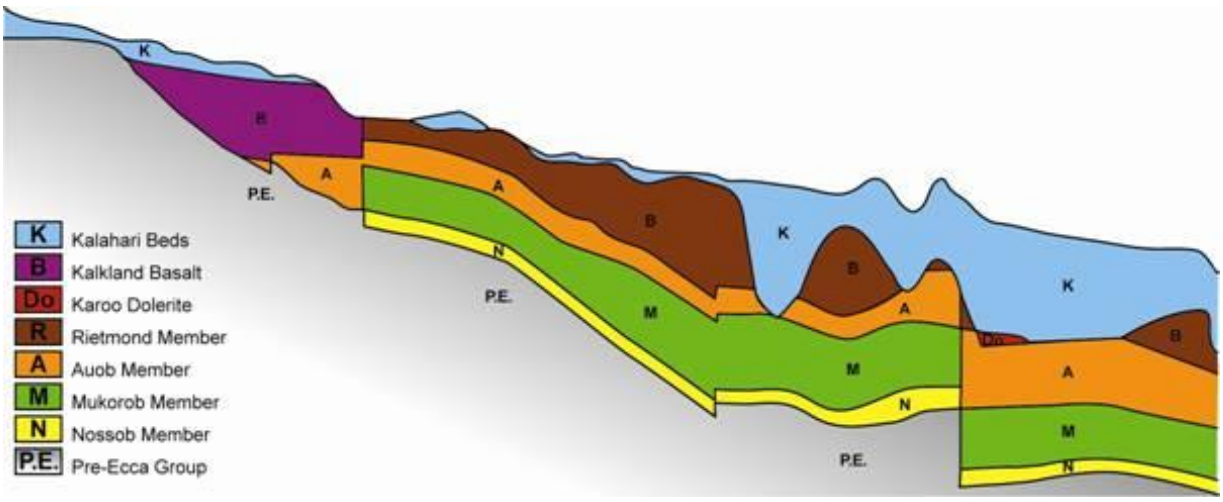


Figure 28: Cross-section through the Stampriet basin *(Courtesy Greg Christellis)*

4.3.4. Aquifer productivity

The aquifer types were grouped into eight classes according to aquifer productivity (Table 3).

The aquifer classes were adopted from Struckmeier and Margat (1995). The classification combines information on aquifer productivity (lateral extent) and the type of groundwater flow regime (intergranular or fissured) (Struckmeier and Margat 1995). This is depicted in Table 4.

Table 3: Hydrogeology and aquifer productivity of rock bodies

Productivity Class / **Aquifer Type**	1. High productivity	2. Moderate productivity	3. General low productivity but locally moderate productivity	4. Generally low productivity
A. Unconsolidated Intergranular aquifers	A1	A2	X	X
A. Fissured aquifers	B1	B2	X	X
B. Karst aquifers	C1	C2	X	X
C. Low permeability formations	X	X	D1	D2
		Denotes an extensive aquifer overlain by cover		

Table 4: Hydraulic characterisation of aquifer classes (Struckmeier and Margat 1995)

Aquifer Category	Specific Capacity (L/s/m)	Transmissivity (m2/d)	Permeability (m/d)	Very aprox. Expected yield (L/s)	Groundwater Productivity
A, B, C	>1	>75	>3	>10	<u>High:</u> Withdrawals of regional importance (supply to towns, irrigation)
A, B,C	0.1 – 1	5 – 75	0.2 – 3	1 – 10	<u>Moderate:</u> Withdrawals for local water supply (smaller communities small scale irrigation etc.)
D1	0.001 – 0.1	0.05 – 5	0.002 – 0.2	0.01 – 1	<u>Generally low productivity but locally moderate productivity:</u> Smaller withdrawals for local water supply (supply through hand pump, private consumption)
D2	<0.001	<0.05	<0.002	<0.01	<u>Generally low productivity:</u> Sources for local water supply are difficult to ensure

The following data constraints affected the development of the approach to assign aquifer productivity that was finally adopted:

- Highly variable data availability in the member countries and complete lack of data from some countries.
- Questionable data quality lack of key data such as coordinates, yield, borehole depth etc.
- Lack of relevant thematic maps such as soil maps and geomorphology information.

Furthermore, certain other characteristics of the project also affected the approach:

- Large size of the SADC region, and the need to present information meaningful at continental scales, with significant generalization of lithology and hydrogeological data inputs.
- Ground verification was not possible within the scope of the project.
- Time constraints (project duration).

The following approach was adopted to assign aquifer productivity:

- Delineate permeable areas of productivity ranging from high to moderate productivity using expert knowledge based on local experience and knowledge. The low permeability formations were grouped into locally moderate productivity and low productivity.
- Ask national contact persons from member countries to verify and update pertinent data to improve the hydrogeological map.

To assign aquifer productivity to the different hydro-lithological units a scheme (Figure 29) was adopted. The Productivity assigned of an aquifer type is based on flow properties (transmissivity) and sustainability (local recharge). As an example, moderate recharge conditions combined with a highly transmissive aquifer will be assigned as 1. The long-term aquifer productivity of hydro-lithological domains is primarily governed by both the inherent lithology properties (i.e. conductive material properties) and water supply (i.e. groundwater recharge to the material). Hydro-lithological domains can be classified by these two basic parameters. Hydro-lithological domains in the upper right corner of the matrix are more productive than those of the lower left corner. Hydro-lithological domains to the left require boreholes over a larger area than the domains to the right.

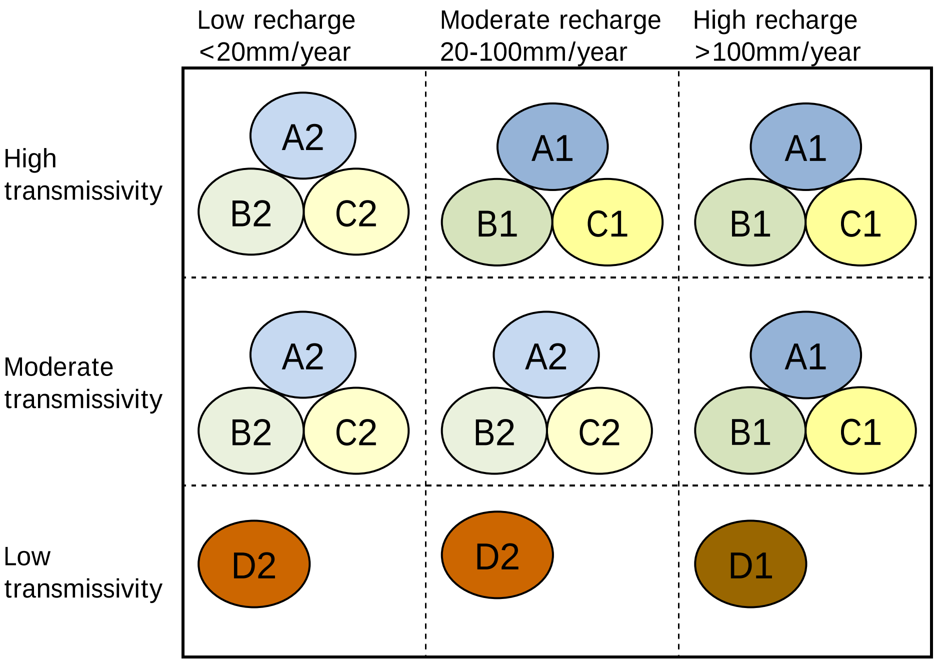


Figure 29: Scheme adopted for assigning aquifer long term productivity to hydro-lithological domains on the SADC hydrogeological map. (refer to Table 3).

The combination between transmissivity and recharge has different significance of aquifer productivity. For instance high transmissivity and low recharge will imply:

- a high short term aquifer yield, and;
- a low long term productivity

Whereas, low transmissivity and a high recharge will imply:

- a high short term productivity from many boreholes
- low short term productivity from a few, boreholes, and;
- a high long term productivity from many boreholes

The water balance must be met in the long run, which implies that the long term aquifer productivity is limited by the magnitude of recharge to the aquifer.

The productivity map should only be seen as a starting point from which countries should be able to update the information whenever new field data becomes available.

The various techniques employed in determining aquifer productivity are technical and require professionals with some relatively good GIS/remote sensing skills. Training of staff from the member countries in such techniques is thus critical in the context of sustainability.

Note that this step was a lengthy process where all available geological and hydrogeological materials were considered for each area (in map terms, a polygon or a set of polygons). In effect, the rock type polygons were overlain, using a GIS or manually, with relevant reference layers (primarily the scanned national hydrogeological maps), and an essentially 'manual', expertise-based decision was made for each area.

This was followed by national contact persons from Member States to verify and update pertinent data to improve the hydrogeological map, reassigning production classes according to improved knowledge, or even re-defining them if necessary

The result was the SADC hydrogeology map (Figure 30).

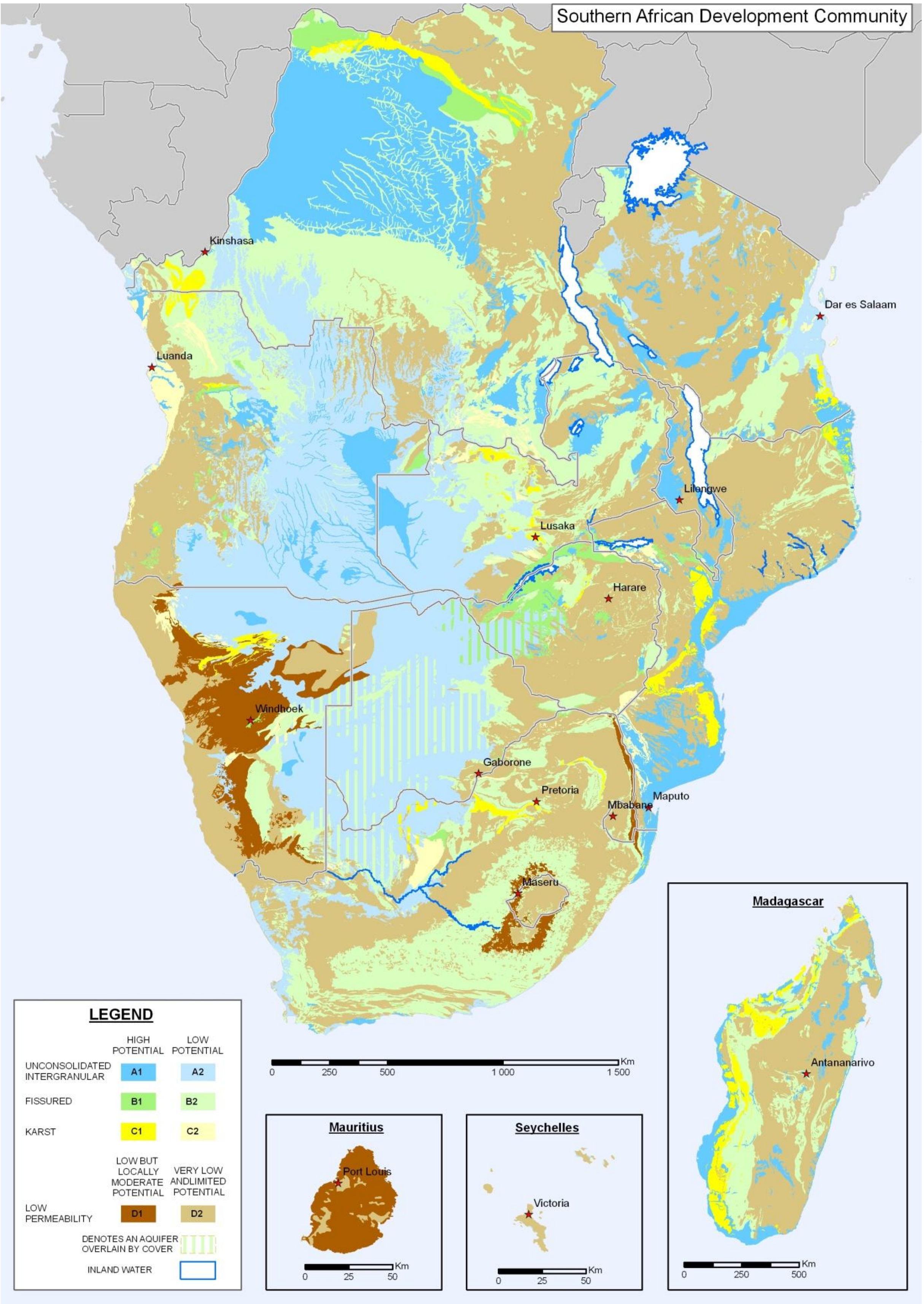


Figure 30: SADC hydrogeology map.

4.3.5. Groundwater quality

Human health can be affected by long-term exposure to either an excess or a deficiency of certain chemicals in groundwater.

Electrical conductivity is a rough indication of groundwater quality: the higher the numbers of ions present in groundwater, the poorer the quality of the water. Electrical conductivity is related to Total Dissolved Solids content. Conductivity measurements can be converted into TDS values by means of a factor, which varies with the type of water. No health-based guideline value is proposed for TDS by the World Health Organisation (WHO), although high EC or TDS affects the taste of groundwater (salinity) and people may object to use of the resource on this basis rather than for health reasons.

Dental and skeletal fluorosis can arise from long-term exposure to high fluoride concentrations. The guideline value of 1.5 mg/litre is set by the WHO (Figure 31)

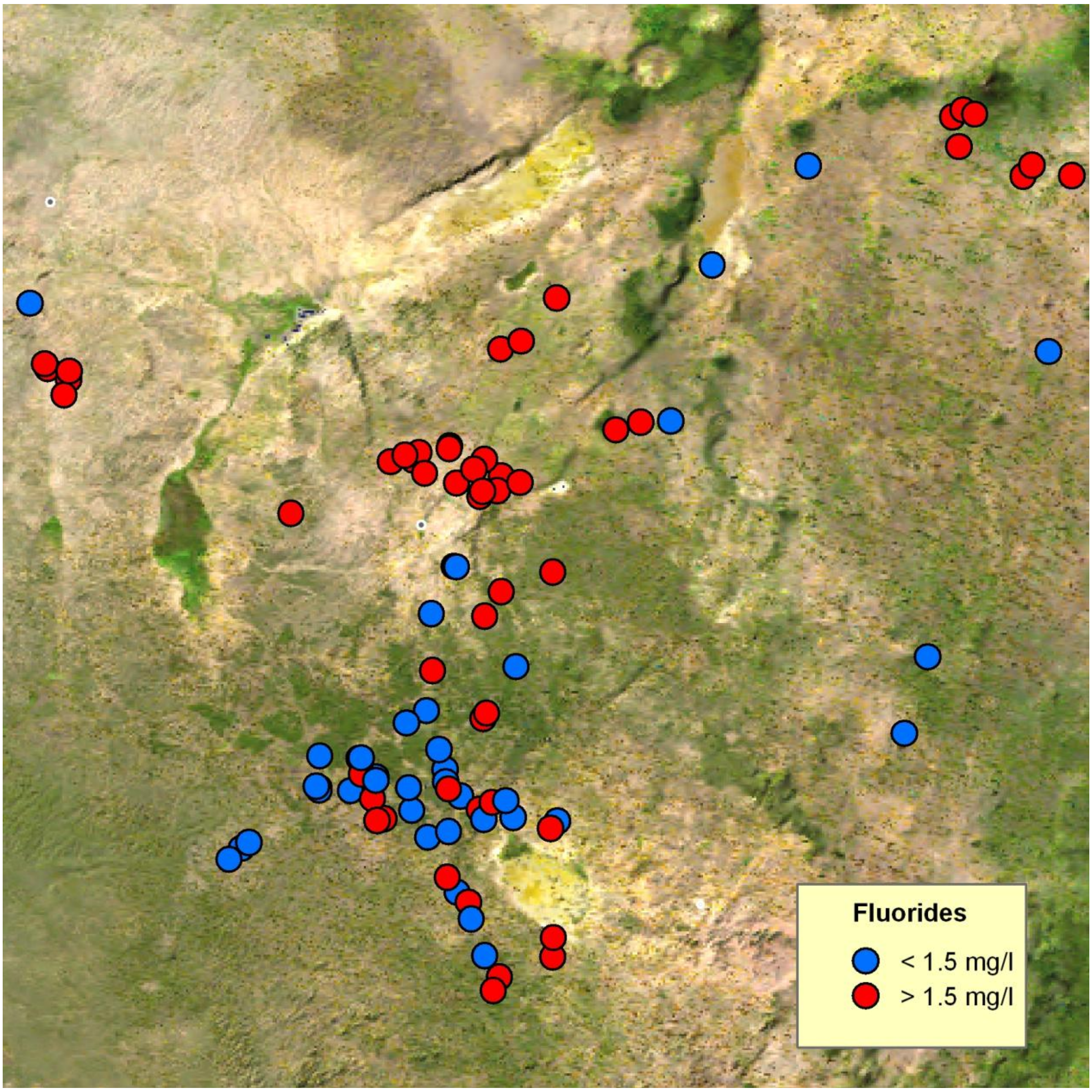


Figure 31: An example of groundwater quality parameter, fluoride, extracted from the borehole database, Central Tanzania.

Nitrate is found naturally in the environment and is an important plant nutrient. Nitrate in groundwater normally results from anthropogenic activities. Some groundwater may also have nitrate contamination as a consequence of leaching from natural vegetation (e.g. Acacia species). The WHO guideline value for nitrate, 50 mg/l (as short term exposure), is to protect against methaemoglobinaemia in bottle-fed infants, known as "blue-baby syndrome".

5. Transboundary aquifer systems

"Transboundary aquifer" or "transboundary aquifer system" means, respectively, an aquifer or aquifer system, parts of which are situated in different States

The law of transboundary aquifers

Many aquifer systems in SADC are relatively low yielding. This applies also to aquifers underlain by national borders. Groundwater movement is governed by the hydraulic properties of the aquifer. In the case of low-yielding aquifers, where the transmissivities are low, the concept of a transboundary aquifer becomes problematic. Groundwater movement is either slow or occurs within disconnected packets (Cobbing, et al. 2008). What constitutes a transboundary aquifer or aquifer system requires further refinement in this case.

The first inventory of African Transboundary Aquifers by hydrogeological experts was produced during a workshop held in the Tripoli, Libya in 2002. This was refined by later sub-regional meeting, under the auspices of the International Association of Hydrogeologist (IAH) and UNESCO Internationally Shared (transboundary) Aquifer Resource Management (ISARM) Programme. UNESCO (2009) identifies the following most important and known transboundary aquifers:

- Coastal Sedimentary basin, DRC
- Congo intra-cratonic basin, DRC
- Karoo sandstone aquifer, Mozambique – Tanzania
- Coastal sedimentary basin, Mozambique – Tanzania
- Coastal sedimentary basin, Angola – Namibia
- Cuvelai Basin, Namibia – Angola
- Northern Kalahari/Karoo Basin, Angola – Botswana – Namibia – Zambia
- Nata Karoo Sub-basin, Botswana – Namibia – South Africa
- Medium Zambezi aquifer, Zambia – Zimbabwe – Mozambique
- SW Kalahari/Karoo Basin, Botswana – Namibia- South Africa
- Ramotswa Dolomite Basin, Botswana – South Africa
- Tuli – Karoo Sub-basin, Botswana – South Africa – Zimbabwe
- Limpopo Basin
- Incomati/Maputo Basin, Mozambique – Swaziland- South Africa
- Coastal Sedimentary Basin, Namibia – South Africa
- Karoo Sedimentary aquifer, Lesotho – South Africa

In the compilation of the SADC hydrogeology map the criteria for delineating transboundary aquifers were adopted as follows:

- Shared by more than one SADC country
- Continuous aquifers
- Sub-basin river boundaries
- SADC hydro-lithological boundaries

The identified transboundary aquifers are given in Figure 32 and Table 5.

The natural extent of these aquifers needs to be verified through detailed investigations.

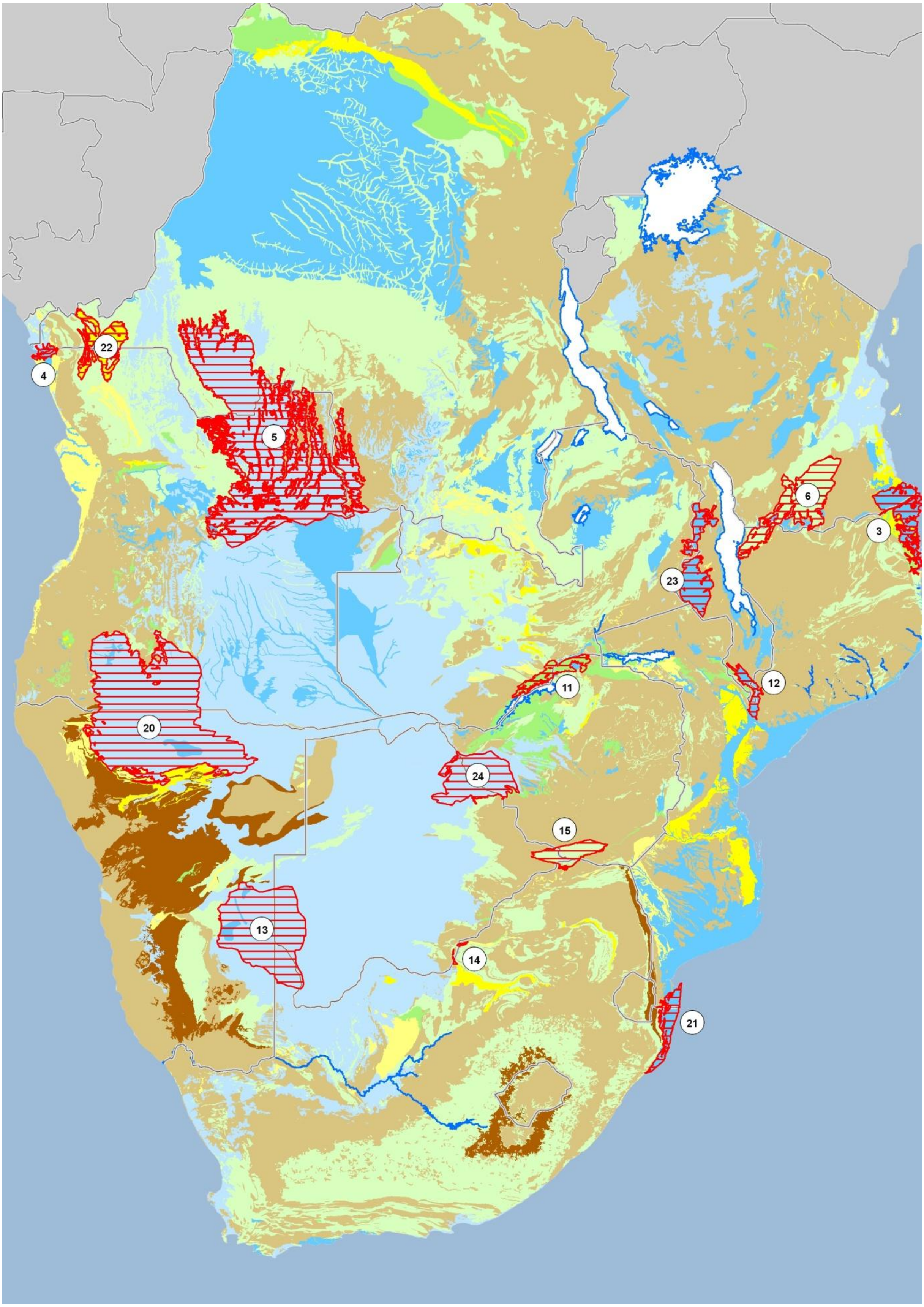


Figure 32: Transboundary aquifers delineated as an outcome of the SADC hydrogeological map compilation. See **Table 5** for codes.

Table 5: Transboundary aquifer names

Name	Code	States
Karoo Sandstone Aquifer	6	Tanzania, Mozambique
Tuli Karoo Sub-basin	15	Botswana, South Africa, Zimbabwe
Ramotswa Dolomite Basin	14	Botswana, South Africa
Cuvelai and Etosha Basin	20	Angola, Namibia
Coastal Sedimentary Basin 1	3	Tanzania, Mozambique
Shire Valley Aquifer	12	Malawi, Mozambique
Congo Intra-cratonic Basin	5	D R Congo , Angola
Coastal Sedimentary Basin 2	4	D R Congo , Angola
Coastal Sedimentary Basin 6	21	Mozambique, South Africa
Medium Zambezi Aquifer	11	Zambia and Zimbabwe
Dolomitic	22	D R Congo , Angola
Sands and gravel aquifer	23	Malawi, Zambia
Kalahari/Karoo Basin	13	Botswana, Namibia, South Africa
Eastern Kalahari/Karoo basin	24	Botswana and Zimbabwe

6. The future of the SADC hydrogeological map and atlas

6.1. Updating the map

The SADC HGM is a general hydrogeological map which provides information on the extent and geometry of regional aquifer systems.

The map is intended to serve as a base map for hydrogeologists and water resource planners, whilst at the same time presenting information to non-professionals. The map is a visual representation of groundwater conditions in SADC and serves as a starting point for the design of more detailed regional groundwater investigations by exposing data and knowledge gaps.

It is important to note that the SADC HGM is published as an interactive web-based map and is not a printed map. The map may thus be easily updated as new information and knowledge becomes available.

Key to updating the map is the improvement of groundwater data sets and information systems in the various countries. There needs to be a concerted effort to correct these shortcomings. A future update of the map requires a bottom-up approach to work with countries to ensure representative datasets are obtained from the various geological domains.

The responsibility for the updating of map currently lies with the Department of Geological Survey of Botswana. It is intended that the responsibilities will be transferred to SADC Groundwater Management Institute, once it is fully functional. However, any update requires need information and data; it remains the responsibility of the SADC Member States to submit this to the hosting agency.

6.2. Recommendations for further studies and development of the map

- Improve field procedures to collect groundwater data and information
- Develop better understanding of the hydrogeological properties of the various geological domains
- The various techniques employed in determining aquifer productivity are technical and require professionals with some relatively good GIS/remote sensing skills. Training of staff from the member countries in such techniques is thus critical in the context of sustainability.
- Aquifer recharge is a complex field that requires high level skills which are lacking in most of the SADC Member States. Staff from Member States therefore needs training in aquifer recharge determination and processing by using established programmes (e.g. WaterGAP Global Hydrology Model WGHM) and RS/GIS).

6.3. Contact persons

The Director
Geological Survey Department
P/Bag 14
Lobatse

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