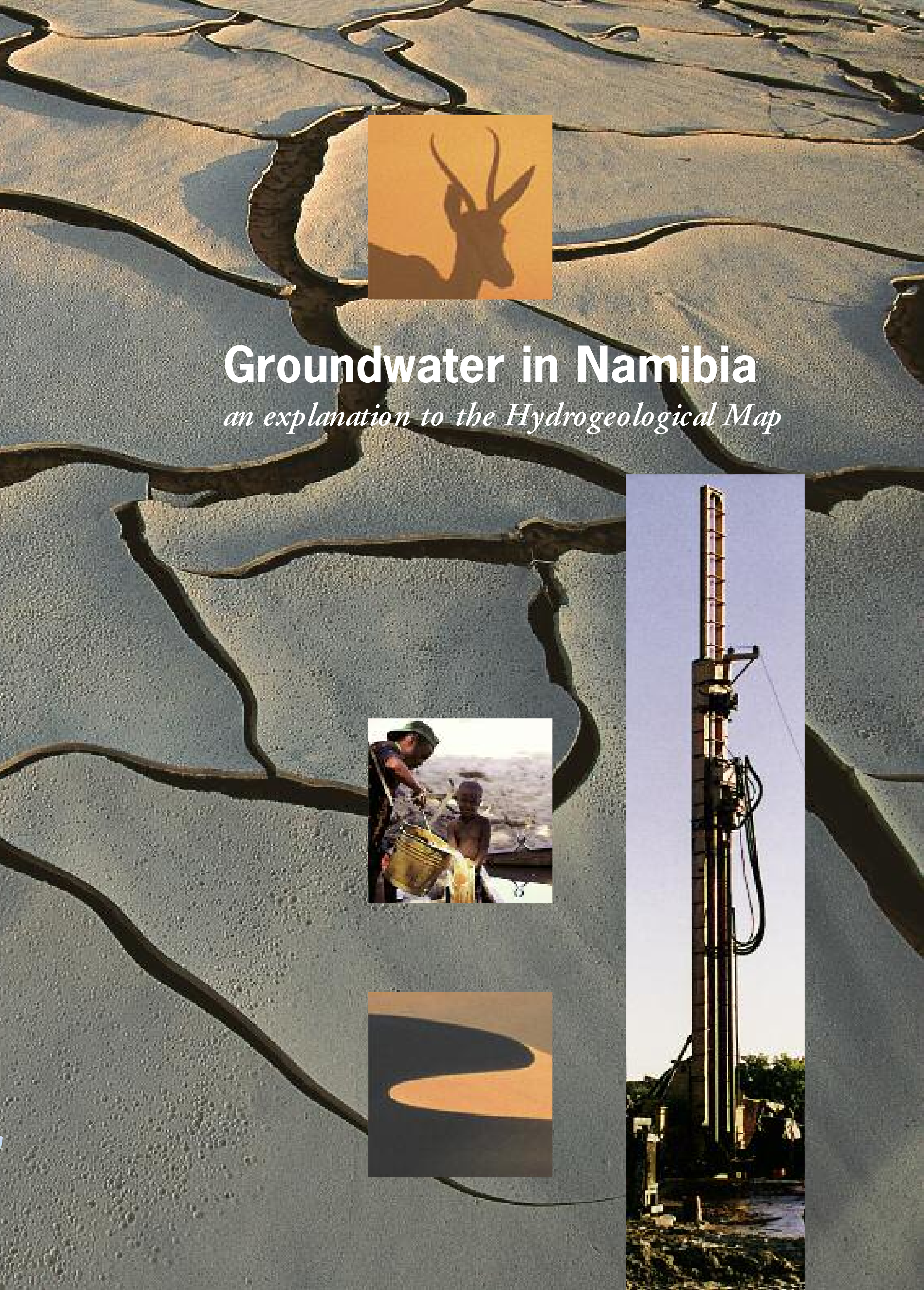
Groundwater in Namibia

an explanation to the Hydrogeological Map




Claudia du Plessis

Groundwater in Namibia
an explanation to the Hydrogeological Map

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(editors)

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under the supervision of the Steering Committee
of the Hydrogeological Map of Namibia Project
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reviewed by Shirley Bethune

This publication complements the Hydrogeological Map of Namibia
at scale 1:1 000 000 prepared as a Namibian – German technical cooperation project
of the Department of Water Affairs, Ministry of Agriculture, Water and Rural Development;
the Geological Survey of Namibia, Ministry of Mines and Energy;
the Namibia Water Corporation and
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Foreword

MAWRD

Honorable Minister
Helmut K Angula

Water is essential for the survival of mankind and the natural environment. Social welfare and economic development cannot be sustained without reliable water supplies, and this is particularly true of arid countries, such as Namibia, where water resources are extremely limited and highly valued as a social and economic good. The early people who settled in Namibia migrated through the arid landscape in the interior of the country to graze their cattle. They found fountains, seeps and springs that provided them with open surface water, and also learned to dig shallow wells in the dry watercourses to find groundwater. Many of our towns, settlements, farms and special places bear the names of the waters that were available to sustain wildlife, man and his livestock.

The name of the town Gobabis is derived from a spring that was called "place of the elephants". In the south of Namibia, the towns of Karasburg, Warmbad and Keetmanshoop were founded at springs, respectively called "Nomsoros" (water between the lime stones), "Gei-ous" (big hot water source) and "Nugoeis" (black mud fountain). In the north, towns have been named after water features, for example Engela (wet place), Okatope (small well), Oshikango (place with many pans).

Although surface waters are available during the rainy season, these normally dry up very soon in the dry winter months. When these resources dried up, the people and their cattle even perished in the severe droughts that occur periodically in Namibia because they did not know about the hidden treasure of groundwater deep underground.

For more than a century, the technology to find and drill for groundwater continued to improve and brought additional benefits such as hydrogeological data collected in a systematic, scientific way. This now provides an excellent opportunity to produce a hydrogeological map for the country. The value of a hydrogeological map is that the available information about the occurrence and magnitude of the groundwater resources in the country can be presented to the general public in a simplified way, but more specifically, it can assist those that need accurate information to direct the development of the country according to the availability of sustainable groundwater resources.

Although the Geohydrology Division in the Department of Water Affairs in the Ministry of Agriculture, Water and Rural Development has long recognised the need for a hydrogeological map, a lack of resources was a major challenge to this objective. In 1996, the Namibian Government approached the German Government for support to prepare a national hydrogeological map. This request was thoroughly evaluated in terms of the availability of data and the need for such a map. A wealth of information already collected about the hydrogeological environment could be used to prepare the map. The need for a hydrogeological map to enhance the future development of a developing country like Namibia was also evident. This convinced the German Government to provide technical expertise to produce the Hydrogeological Map of Namibia.

After two years of close cooperation between staff of the Federal Institute of Geosciences and Natural Resources in Germany, the Ministry of Agriculture, Water and Rural Development, the Geological Survey of Namibia and the Namibia Water Corporation, the Hydrogeological Map of Namibia has become a reality.

In my view, the Hydrogeological Map of Namibia and this explanatory book "Groundwater in Namibia" that accompanies the Map, will assist planners, developers and entrepreneurs to direct their activities in such a way that our valuable, yet vulnerable, groundwater sources will be utilised sustainably to facilitate socio-economic development for the benefit of all the people in this country now and in the future.

Helmut K Angula
Minister of Agriculture, Water
and Rural Development

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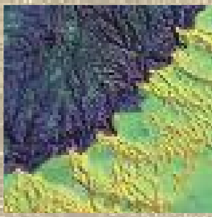


The Groundwater Map

Executive Summary

Water is life, but in a country as dry as Namibia, water resources are often scarce and unreliable. Surface water availability is closely linked to a rainfall pattern that is extremely inconsistent in both time and space. Too much rain can cause floods that are difficult to master and during droughts surface waters evaporate quickly. Groundwater resources, a “hidden treasure” underground, are more reliable, widespread and naturally protected against evaporation. The groundwater stored in the pore spaces between sand grains and in voids of rocks has a regulating function: it can be abstracted during dry periods and filled up again by recharge during good rains.

Namibia, the driest country in Africa south of the Sahara, depends largely on groundwater. Over the past century, more than 100 000 boreholes have been drilled. Half of these are still in operation and produce groundwater for industrial, municipal and rural water supply. They provide drinking water to man, livestock and game, irrigation water for crop production and supply distant mines. The advantage of using groundwater sources is that even isolated communities and those economic activities located far from good surface water sources like mining, agriculture and tourism, can be supplied from groundwater over nearly 80 % of the country.

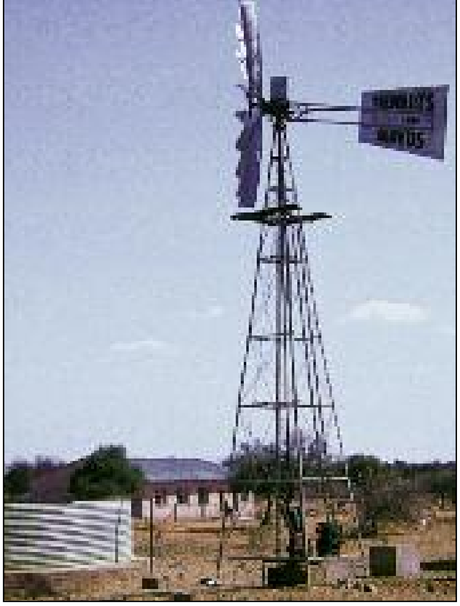
Despite considerable investment in drilling, borehole design and construction as well as pumping and maintenance, groundwater is usually the most economical way of supplying water. However, groundwater resources, being closely associated with underground rock types that vary with the geological situation, are unevenly distributed across the country. There are only a few favourable places where high volumes of groundwater can be sustainably abstracted, but fortunately there are also few places where no groundwater is found at all. But even if there is enough groundwater in a region, it might be unfit for human use because of its poor quality. The north-western part of the Cuvelai-Etosha Basin and the south-eastern part of the Stampriet Basin, the so-called salt block, are prominent examples.

This book “Groundwater in Namibia” and the attached “Hydrogeological Map of Namibia” at a 1:1 000 000 scale, are the result of a two years’ technical cooperation project of the Republic of Namibia and the Federal Republic of Germany. The Map and Book synthesise the groundwater related data, information and knowledge available in Namibia. The project enjoyed the cooperation of experts from the Department of Water Affairs (DWA) in the Ministry of Agriculture, Water and Rural Development; from the Geological Survey of Namibia (GSN) in the Ministry of Mines and Energy; from the Namibia Water Corporation Ltd. (NamWater); from the Federal Institute for Geosciences and Natural Resources (BGR) on behalf of the German Ministry for Economic Cooperation and Development (BMZ), and many other hydrogeological and geological experts in the country.

The groundwater situation in Namibia is outlined in detail in the chapter “Hydrogeological Framework”. Compilers of the Map identified twelve main hydrogeological units based on their coherent geological and hydrogeological conditions. The chapter presents the status of the groundwater resources in these groundwater basins or units, their quantitative and qualitative aspects, and their present-day use.

Good data were usually available for the Groundwater Supply Schemes (109 sites) run by NamWater and certain Municipalities listed in Annex 1. In other areas, boreholes representative of the hydrogeological situation in their vicinity were added (see Annex 2). The rest of the country was classified into aquifers, aquitards and aquicludes using the data available in the databases of DWA, GSN and NamWater, records and documentation as well as the local expertise of numerous groundwater experts, most of whom contributed voluntarily to the Map and the Book. Despite this wealth of information, knowledge about groundwater is still sparse or insufficient for some areas. Here the Map and the Book can help focus future investigations and programmes.

Whether or not groundwater can be stored and the way it flows is largely determined by the types of rocks underground. About half (48 %) of the country is covered by unconsolidated deposits that are potential porous aquifers and the rest is made


DWA Archive

Windpump and borehole installation

up of hard rocks, more or less fractured. Fractured hard rocks and porous unconsolidated rocks are regarded as aquifers, only if they store extractable groundwater in an appreciable quantity. Only groundwater-producing rock bodies, in which borehole yields generally exceed 3 m^3/h, are classified as aquifers and are shown in blue or green on the Map. Those with borehole yields between 3 and 0.5 m^3/h are aquitards, and are shown in light brown, while rocks in which very little groundwater is found (borehole yields less than 0.5 m^3/h) are shown as dark brown aquicludes. Only 42 % of the country overlies aquifers, of which 26 % of the area contains porous aquifers and 16 % fractured aquifers. Within these aquifers, the borehole yields exceed 15 m^3/h only over some 14 000 km^2 or 3 % of the total territory, making these highly productive aquifers and strategic targets for groundwater supply. Not surprisingly, most of these areas are already declared groundwater control areas.

Wherever known, quantitative information about aquifer parameters, groundwater volumes and water balance figures have been provided in the text. However, detailed figures exist only in a few places where groundwater models have been established, e.g. in the Grootfontein and Tsumeb areas and in the Stampriet Artesian Basin.

Although Namibia is an arid country, its finite water resources are sufficient to sustain continuous growth and steady development of the Nation. There are however great variations in the availability of water. At the southern, northern and north-eastern borders where surface water is available throughout the year from perennial rivers, there is an excess rather than a shortage of water, although this is shared with neighbouring countries. The rest of the country either relies on dams constructed in ephemeral rivers that have low safe yields in comparison to their total volume, because of drought and high evaporation losses, or on groundwater. The total, overall groundwater resources are sufficient to assure long-term water supply if used sustainably, yet there are great regional variations. In many areas, groundwater conditions are unfavourable due to limited water availability, little and unreliable recharge, low borehole yields, great depths, poor groundwater quality and high risks of contamination. Other areas are favourable, sitting on high-yielding, very productive aquifers that contain more water than farmers and communities presently need. Numerous small springs, fountains and seeps throughout the country sustain wildlife, man and livestock in an otherwise arid environment.

Groundwater resources should be preserved and protected as an underground treasure, as a strategic reserve for drinking water supply in prolonged periods of drought and for future generations. It must not be spoiled by over-exploitation now, just because the water "is there", and care should be taken not to contaminate them with pollutants.

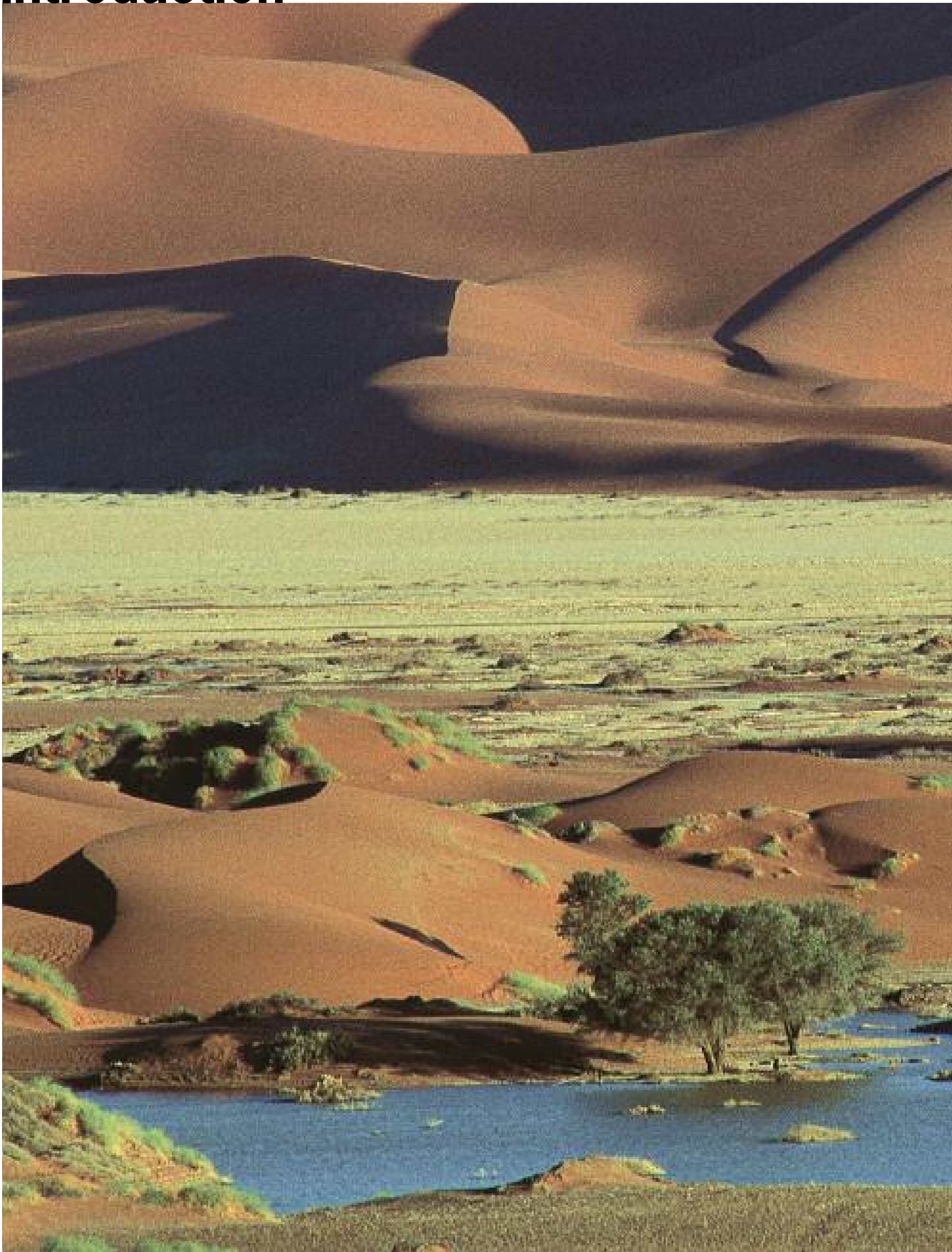
The Hydrogeological Map and this Book summarise the information on groundwater in Namibia, and pinpoint where groundwater is sparse or abundant. This information, judiciously used, can provide the backbone for the equitable distribution, sound development and long-term sustainable management of Namibia's groundwater resources, and the protection of groundwater resources from degradation in quantity and quality. As such, these results of the Hydrogeological Map of Namibia Project are a milestone in groundwater-related work in Namibia and a cornerstone for a sustainable, environmentally-sound water development strategy for Namibia.

G CHRISTELIS, W STRUCKMEIER

Cronje Loftie-Eaton

Water is life – but it can be dangerous and destructive

Introduction



Water in Namibia and rationale for a Hydrogeological Map Project

Claudia du Plessis

In arid areas, where rainfall is limited and surface runoff is only available during the rainy season, man has learnt through experience that there is water underground that can be used during the dry season. Thus, groundwater has played an important role in the development of Namibia.

Groundwater resources have been recognised and used for drinking purposes since humans settled in Namibia. The preferential areas of settlement were near springs or fountains from which groundwater naturally seeped into ponds or even formed the beginning of small perennial watercourses. Hauchabfontein, Sesfontein and Kowarib are well known examples. Even the capital city, Windhoek, owes its origin to the availability of safe groundwater from flowing springs. Later, springs and ponds were deepened by hand to reach more water. Wells were also dug into the dry watercourses where no springs existed, but where the groundwater was shallow. Today, groundwater resources lying hundreds of metres below the surface, are tapped by deeply drilled boreholes.

When Namibia became a Protectorate of the German Empire in 1884, momentum was given to the development of agriculture, mining and infrastructure such as railways, roads and water supplies. As the population grew, permanent towns and farms were established and it soon became apparent that more reliable, assured water supplies were required to support future economic activities in Namibia.

Wilhelm Struckmeier

Old drilling machine for groundwater boreholes

In October 1896, Dr Rehbock was commissioned by the German Government to investigate the occurrence, availability and utilisation of the water resources in the country. In 1897, he distributed the first rain gauges to farmers to better understand the hydrology of the country by obtaining information about rainfall and runoff. The advice in the report to his Government gave more direction to water resource development in Namibia.

In 1903, the first drilling machine arrived in the country and by 1906 there were two drilling units, one for the south and one for the north. They operated under the control and supervision of a geologist, Dr Lotz, who conducted the search for groundwater in an organised manner. This improved technology and expertise brought into the country, made it possible to drill boreholes for groundwater at greater depths and in water bearing geological formations that had previously been inaccessible. In 1906, Dr Range, a hydrogeological expert, was sent to Namibia to assist with the groundwater development programme and he takes credit for recognising the artesian conditions of the Stampriet basin. By 1913, a geographer, Prof Jaeger, used the available information on surface runoff and groundwater to compile the first water register for the country.

After the First World War, a new Administration for the Territory of South West Africa was established and an Irrigation Department with a Boring Division, directed by a drilling engineer, was created. The duty of this Department was to find groundwater sources suitable for stock farming and irrigation. The activities of the Boring Division, as well as the work of many geologists, hydrogeologists, water diviners and private drilling contractors since then, made it possible to extend the availability of groundwater sources to many places in the country where there had previously been no water available for stock drinking and human consumption. This increased availability of groundwater secured the development of stock farming on the grasslands in the more remote areas of Namibia, and the development of stronger boreholes made it possible to sustain the larger towns and settlements, as well as other important economic activities such as mining, industry and small-scale irrigated agriculture.

Whenever there is a scarcity of water, it is mainly due to low rainfall. The distribution of rainfall across the Southern African subcontinent is the lowest along the south-western Atlantic coast, an area largely covered by the territory of Namibia (refer to the “Rainfall and Watershed” inset map on the Hydrogeological Map). In addition to the general paucity of precipitation, rainfall events are extremely unreliable, variable and unevenly distributed in space and time over the landscape. Furthermore, the prevailing high temperature in the rainy season and huge evaporation losses make Namibia not only the driest country in southern Africa, but most probably in the whole of the Southern Hemisphere.

In order to utilise surface runoff, dams have been built to capture and store water from the floods during the rainy season. However, the assured sustainable safe yield of such dams is dependent on unreliable and unfavourable hydroclimatic conditions. The availability of surface water resources can therefore not be guaranteed, even with creation of the most appropriate facilities. The construction of storage reservoirs or dams is also limited by the topography of the landscape and there are large areas in Namibia where the terrain is too flat to build viable dams to harness surface runoff.

It may be reasoned that in areas where surface water use is limited, one rather expensive option is to import the water required over long distances from other surface or groundwater sources, however, the use of local groundwater sources is still the most appropriate and cost-effective way to provide water in most of these areas.

Wilhelm Struckmeier

Omatako Dam, a dam site vulnerable to high evaporation

The weather systems, rainfall, surface runoff and open water bodies are the visible components of the water cycle. However, the surface water that infiltrates into the ground fills up the voids and pore spaces of the rock formations making up the crust of the earth, and this accumulation of water in the aquifers below the surface is not only invisible, but an integral part of the hydrological cycle. The availability of water resources in Namibia is reflected in the table below.

Like surface water sources, groundwater can also be regenerated and replenished by rainwater filtering into the ground. The magnitude and sustainable yield of the groundwater sources are therefore determined by the size and extent of the aquifers, the conditions that facilitate the rate of recharge to the aquifers and the potential of the hydroclimate to produce rainfall and runoff.

Water availability

Source	Volume (Mm^3/a)	Remark
Groundwater	300	Estimated long-term sustainable safe yield
Ephemeral Surface Water	200	Full development at 95 % assurance of supply
Perennial Surface Water	150	Presently installed abstraction capacity
Unconventional	10	Reclamation, re-use, recycling
Available Resources	660	

However, there are also fossil groundwaters that have accumulated tens of thousands of years ago in water-bearing aquifers when the climate in the southern African region was much wetter and a large lake covered areas in northern Namibia and southern Angola where the Cuvelai Basin is located today.

In order to find groundwater, more than 100 000 boreholes have been drilled, and of these a large number have either come up dry or dried up over time. It is estimated that there are more than 50 000 production boreholes in use in the country. Groundwater is pumped from these installations for domestic, livestock and wildlife consumption, as well as for mining, industrial operations and irrigation.

The only assured water supply from surface water is lim-

Orange River at the Noordoewer Bridge

Wilhelm Struckmeier

ited to the perennial rivers on the northern and southern and borders of Namibia, but this water must also be shared with the countries neighbouring Namibia. The country is thus highly dependent on groundwater because the surface water sources in the interior of Namibia are unreliable. The dependence on groundwater is accentuated during prolonged periods of drought, when surface water sources tend to dry up.

The advantage of using groundwater sources in Namibia is that it is possible to supply water to isolated communities, and for economic activities like mining, industry and agriculture over nearly 80 % of the country. Without groundwater, development in many of these cases would have been impossible due to the need to import prohibitively expensive water over long distances via canals or pipelines. About 45 % of the water supplied to towns, villages and farms in Namibia comes from boreholes or springs. It is also interesting to note that 45 % of the water used in agriculture comes from groundwater sources. The table below shows the use of the water resources in Namibia by each major consumer group.

Thus it is obvious that Namibia could not survive without using its precious groundwater resources. However, although groundwater had been sought and used for more than a century, the occurrence, magnitude and potential of groundwater resources are still not fully known. This is particularly true in remote areas where the demand for water is small and little groundwater investigation had been done. Even in areas of intensive groundwater abstraction, the knowledge about the water balance or recharge versus abstraction, is often insufficient due to the short period of monitoring of these aquifers (in many cases less than 50 years). This makes it difficult to predict the long-term assured, sustainable, safe yield of an aquifer. Each major aquifer is operated according to an aquifer management plan. The behaviour of the aquifer is closely monitored, and an appropriate management strategy adopted to ensure the sustainable utilisation of the aquifer.

Use of water resources per consumer group in 2000

Consumer Group	Demand (Mm^3)	Source of Supply *					
		Perennial Rivers		Ephemeral Rivers		Groundwater	
		(Mm^3)	(%)	(Mm^3)	(%)	(Mm^3)	(%)
Domestic**	73	18	25	20	27	35	48
Stock	77	14	18	3	4	60	78
Mining	14	8	57	1	7	5	36
Irrigation	136	60	44	41	30	35	26
Total	**300**	**100**	**33**	**65**	**22**	**135**	**45**

* The unconventional water sources are included in the ephemeral and groundwater sources

** Industrial and tourism use is included in domestic use because it is only about 4 % of the total water consumption in Namibia

It is also clear that Namibia has a “hidden treasure” of groundwaters, and these resources have to be identified and mapped for the whole country to provide a comprehensive basis for the utilisation of groundwater in development planning. All natural resources and how they function must be well known and fully understood, and this knowledge taken into account in any national development strategy if planners want to make optimum use of the assets provided by nature. Equitable and sustainable development, as spelled out in the Constitution of Namibia, includes the proper and wise use of all natural resources including groundwater, to supply the water needed without harming the environment.

Information about the occurrence of groundwater and the magnitude of groundwater resources have been gathered in Namibia for more than a century, but all this knowledge had never been collated and presented in a way that the general public and scholars can access, appreciate and understand.

The Hydrogeological Map of Namibia at scale 1:1 000 000, provides an overview of the groundwater situation in the whole country. It shows the aerial extent of the rock bodies containing groundwater and their potential. Moreover, it depicts the hydrodynamic features such as the groundwa-

Wilhelm Struckmeier

Drilling is required to know more about groundwater resources

ter flow direction, depth to groundwater, artesian areas, and major groundwater quality restrictions. Information on installations for the abstraction of water (water supply schemes, irrigation schemes), as well as the distribution and transfer of water (canals and pipelines) are portrayed, too. The Map integrates all this complex and interdependent information in an easily readable form.

There are many important reasons why a Hydrogeological Map for Namibia and this explanatory book "Groundwater in Namibia" were prepared. The Map and this book will greatly improve the knowledge and understanding of the groundwater situation in Namibia. It will create an awareness of a natural resource that is vulnerable, but vital for water supply in the country. The Map will also serve as a guide to national development strategies aimed at the sound and sustainable development of the Nation's natural resources. However, a Hydrogeological Map is never complete and the inset map on the "density of boreholes" clearly shows that there is a lack of information in certain areas. This will certainly encourage further investigations into those groundwater resources that are not yet well known. The same applies to the inset map on the "Vulnerability of the groundwater resources" in Namibia. More studies in this field are also vital as there is no hope of recovery if an aquifer in an arid area is polluted. The work that has been done on the Map and this book provides information, creates awareness, gives guidelines for development, and illustrates some of the major challenges that face water resource managers now and in future.

P HEYNS, W STRUCKMEIER

FURTHER READING

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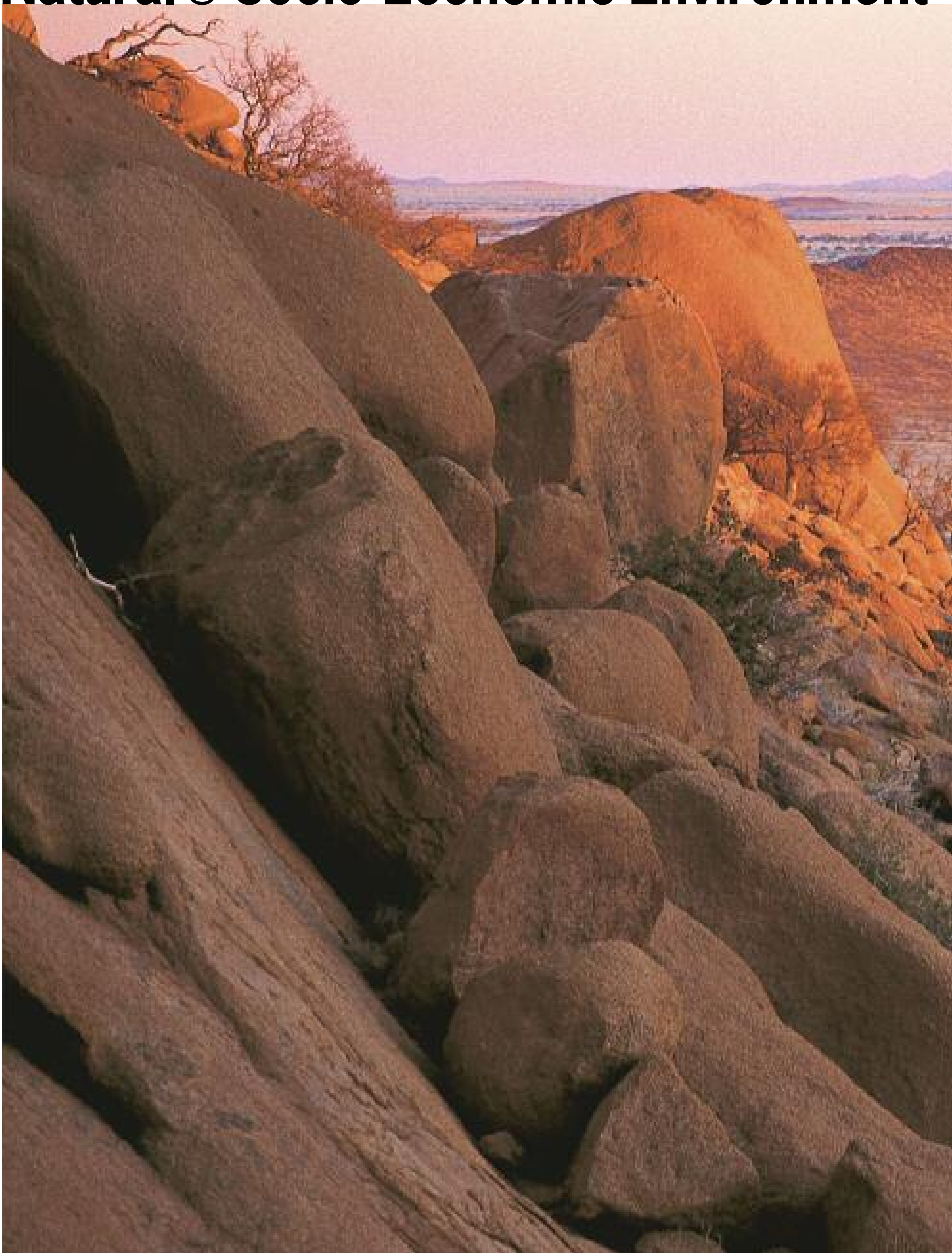
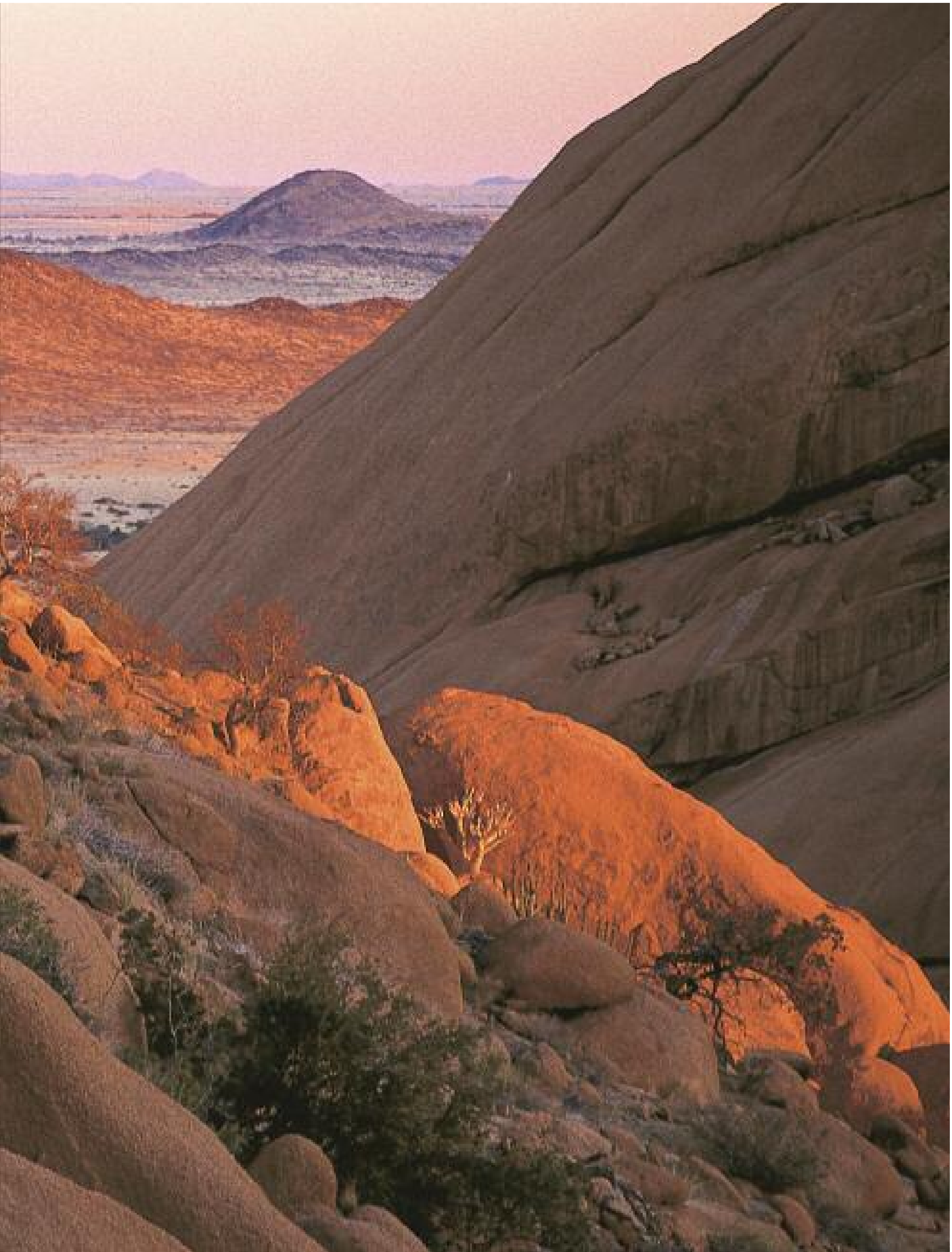
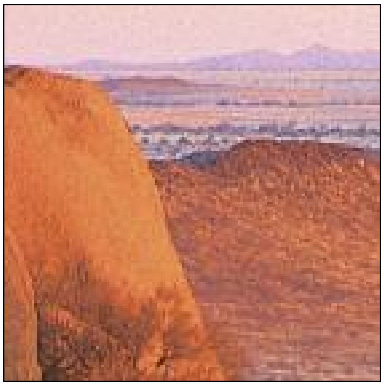
Natural & Socio-Economic Environment





Wynand du Plessis

Geology



Namibia's varied geology encompasses rocks of Archaean to Cenozoic age, thus covering more than 2 600 million years (Ma) of Earth history. Nearly half of the country's surface area is bedrock exposure, while the remainder is covered by young surficial deposits of the Kalahari and Namib Deserts.

Metamorphic inliers consisting of highly deformed gneisses, amphibolites, meta-sediments and associated intrusive rocks occur in the central and northern parts of the country, and represent some of the oldest rocks of Palaeoproterozoic age (ca. 2 200 to 1 800 Ma) in Namibia. The Kunene and Grootfontein Igneous Complexes in the north, the volcanic Orange River Group and the Vioolsdrif Suite in the south, as well as the volcano-sedimentary Khoabendus Group and Rehoboth Sequence also belong to this group.

Stratigraphical units in Namibia

Era	Formation	Namibian Classification	
Cenozoic < 65 Ma	Cretaceous to Quarternary < 135 Ma	< 135 Ma	Cenozoic Sediments Post-Karoo Complexes
Mesozoic 65-250 Ma			
Paleozoic 250-540 Ma	Permian to Jurassic 135-300 Ma	135-300 Ma	Karoo Sequence
	300-500 Ma	Erosion	
	Cambrian 500-540 Ma	Namibian to early Cambrian 500-1000 Ma	Nama Group Damara Sequence Gariep Complex
Precambrian > 540 Ma	Neoproterozoic 540-1000 Ma		
	Mesoproterozoic 1000-1600 Ma	Middle to late Mokolian 1000-1800 Ma	Gamsberg Granite Fransfontein Suite Sinclair Sequence Namaqualand Complex Rehoboth Sequence
	Paleoproterozoic and Archaean > 1600 Ma	Vaalian to early Mokolian > 1800 Ma	Elim Formation Khoabendus Group Vioolsdrif Suite Orange River Group Mooirivier Complex Neuhof Formation Hohewarte Complex Abbabis Complex Grootfontein Complex Huab Complex Kunene Complex Epupa Complex

The Mesoproterozoic (1 800 to 1 000 Ma) is represented by the Namaqualand Metamorphic Complex, which comprises granitic gneisses, metasedimentary rocks and magmatic intrusions, and by the volcano-sedimentary Sinclair Sequence of central Namibia, with associated granites (e.g. Gamsberg Granite Suite).

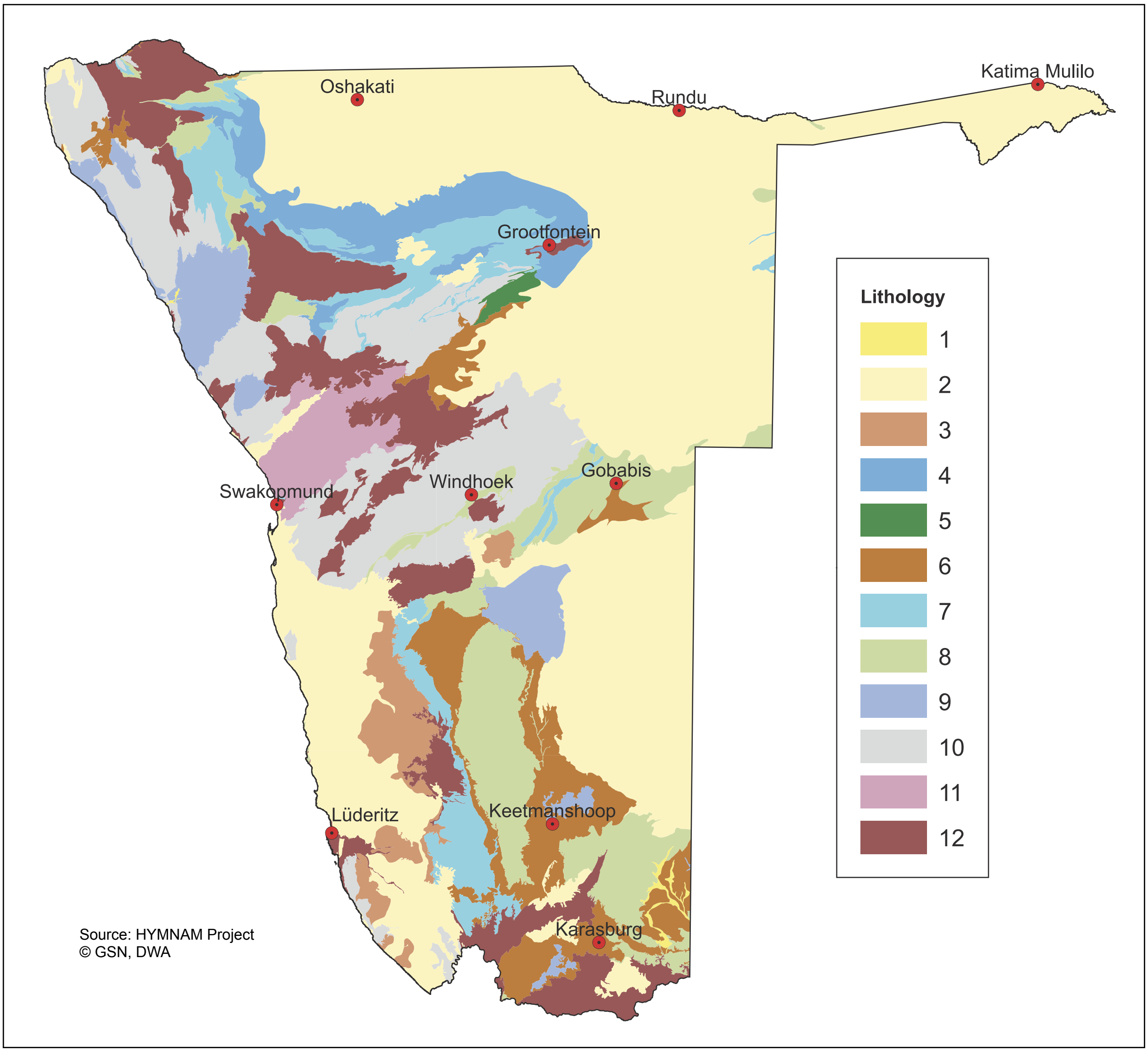
The coastal and intra-continental arms of the Neoproterozoic Damara Orogen (800 to 500 Ma) underlie large parts of north-western and central Namibia, with platform carbonates in the north and a variety of meta-sedimentary rocks pointing to more variable depositional conditions further south. Along the south-western coast, the volcano-sedimentary Gariep Complex is interpreted as the southern extension of the Damara Orogen. During the later stages of orogenic evolution, the shallow-marine clastic sediments of the Nama Group, which covers much of central southern Namibia, were derived from the uplifted Damara and Gariep Belts.

Sedimentary and volcanic rocks of the Permian to Jurassic Karoo Sequence occur in the Aranos, Huab and Waterberg Basins, in the south-eastern and north-western parts of the country. They are extensively intruded by dolerite sills and dyke swarms, which in association with predominantly basaltic volcanism and a number of alkaline sub-volcanic intrusions, mark the break up of Gondwanaland and the formation of the South Atlantic ocean during the Cretaceous.

The currently last chapter of Namibia's geological history is represented by the widespread Tertiary to recent (< 50 Ma) sediments of the Kalahari Sequence.

The main rock types

Based on their hydrogeological characteristics, the extremely varied lithologies occurring in Namibia were grouped into 12 main units for the Hydrogeological Map. While stratigraphic positions and spatial distribution were taken into consideration, the main focus was placed on the groundwater potential of the rocks. The resulting sub-



Source: HYMNAM Project
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Simplified lithological map of Namibia

division is therefore quite different from the lithological units shown on the Geological Map of Namibia.

The following units were established:

(1) Sand and gravel, valley deposits (alluvium)
(2) Unconsolidated to semi-consolidated sand and gravel, locally calcrete
(3) Unconsolidated to semi-consolidated sand and gravel, locally calcrete; with scattered bedrock outcrops
(4) Calcrete
(5) Sandstone
(6) Shale, mudstone, siltstone
(7) Limestone, dolomite, marble
(8) Non-porous sandstone, conglomerate, quartzite
(9) Volcanic rocks (Karoo and younger)
(10) Metamorphic rocks, including quartzite and marble bands
(11) Metamorphic rocks, including quartzite and marble bands; with granitic intrusions
(12) Granite, gneiss, old volcanic rocks

Unit 1, "Sand and gravel, valley deposits (alluvium)" comprises the young infill in valleys and some courses of ephemeral rivers where they are extensive.

Unit 2, "Unconsolidated to semi-consolidated sand and gravel, locally calcrete" occurs abundantly in the Namib Desert between Walvis Bay and Oranjemund, and contains the Cenozoic sediments of the Namib Desert. Further north, this unit occurs east of Terrace Bay and south of the Kunene River mouth, where dunes are locally developed. Infill of the Kalahari Basin, which covers the entire Kalahari Sandveld, the Owambo Basin, as well as the Kavango and Caprivi regions, also belong to this unit.

In the south, between Tses and Keetmanshoop, sandstones of the Auob and Nossob Members of the Prince Albert Formation, Karoo Sequence, that occur along the Weissrand Escarpment have also been included in this unit, because they frequently form a joint groundwater system together with the overlying Kalahari of the Stampriet Basin.

In the Namib south of Lüderitz, as well as in the area east of the main Namib sand sea close to the Great Escarpment, the unconsolidated to semi-consolidated sediments show scattered bedrock outcrops, which range from small hills to prominent inselbergs composed of mainly Proterozoic lithologies. These areas fall into unit 3, "Unconsolidated to semi-consolidated sand and gravel, locally calcrete, with scattered bedrock outcrops".

Unit 4, "Calcrete" comprises a white, flat-lying surface limestone which is commonly developed in warm, arid and semi-arid regions, where it forms by solution and redeposition of calcium carbonate by meteoric waters. The lime forms a hard cement to sand and gravel beds, and can even replace pre-existing material. Such calcretes have a large distribution in the area of Grootfontein and along the southern margin of the Etosha Pan. They also extensively cover some valley infills. Most of the calcretes have been mapped by remote sensing methods from satellite images, since they form very important hydrogeological units (see Box on "Calcrete").

Unit 5, "Sandstone" occurs in the Otjiwarongo area south of the Waterberg Fault, where they belong to the flat-lying aeolian Etjo Formation of the Karoo Sequence.

Unit 6, "Shale, mudstone and siltstone" forms part of the flat-lying Permian to Jurassic Karoo Sequence in the Stampriet, Huab, Waterberg and Owambo Basins in the south-eastern and north-western parts of Namibia. As part of Gondwanaland, southern Africa initially occupied a position close to the south pole, and a huge ice sheet covered the region. Basal glacial rocks of the lower Permian Dwyka Formation were deposited before the Dwyka glaciation ended approximately 280 million years ago, when plate tectonic movements brought southern Africa to a more moderate climatic realm. The melting ice sheet provided ample water to create an environment with huge lakes and rivers, and the Dwyka Formation is overlain by lacustrine grey to green shales, mudstones, limestones, sandstones and coal-bearing shales of the Prince Albert Formation. Mid-Permian rocks in the Stampriet Basin consist of 600 metres of shales with thin limestone layers overlain by shale and sandstone. In the Huab Basin, mid-Permian rocks are represented by purple shales and sandstones. Mudstones also occur within the Omingonde Formation of the Waterberg which in addition comprises red conglomerates, sandstones and grits up to 600 metres thick. In addition, shales of the Fish River Subgroup, Nama Group, a southern molasse, and the Mulden Group, a northern molasse, both to the Damara Orogen, belong to this unit (6), termed "Shale, mudstone, siltstone".

Jürgen Kirchner

View from the Gamsberg looking north-west to the Namib

Unit 7, "Limestone, dolomite, marble" comprises rocks of the Neoproterozoic Damara Orogen which were deposited in an ocean formed during successive phases of intra-continental rifting, spreading and the formation of passive continental margins. The marbles of the Karibib Formation accumulated in a shelf area in north-western central Namibia, while the thick succession of dolomites and limestones of the Otavi Group was deposited on a northern platform and today crop out in fold structures between Grootfontein and Opuwo. The Naukluft Nappe Complex contains appreciable quantities of flat-lying limestones, and therefore also belongs to this unit, as well as limestones of the Nama Group which were deposited in a shallow syntectonic foreland basin of the Damara Orogen.

Unit 8, “Non-porous sandstone, conglomerate, quartzite” forms a unit which was mainly deposited during Damaran times. It comprises the basal Nosib Group of the Damara Sequence which was laid down in, or marginal to, intracontinental rifts, and consists of quartzite, arkose, conglomerate, phyllite, calc-silicate and subordinate limestone, as well as the deep water sediments of the Auas Formation deposited on the edge of a narrow developing ocean. This unit further contains the flat-lying basal and upper sandstones of the Nama Group of southern Namibia.

A sequence of the 180 million year old basalts of the Kalkrand Formation, that are about 360 metres thick, occur in the Mariental area. Volcanic rocks of the Etendeka Formation in north-western Namibia have ages of about 135 million years. Both formations are flat-lying. Extensive dolerite sills and dyke swarms are related to the volcanic rocks which have formed in connection with the continental break up of Gondwanaland and form unit 9 “Volcanic rocks (Karoo and younger)”.

Many different, highly folded rock types of Mokolian and Namibian ages are included in unit 10 “Metamorphic rocks, including quartzite and marble bands”. These extend from the Gobabis area to the Gamsberg region and then southwards to Helmeringhausen.

The 1800 million year old Rehoboth Sequence is thought to have formed in the back-arc basin of a magmatic arc and comprises schist, phyllite, amphibolite and quartzite. Rocks of the Sinclair Sequence accumulated within an intracontinental rift. Deposition of quartzites took place in narrow fault-bounded troughs in today’s Helmeringhausen-Solitaire area after a cycle of magmatic activity. Damaran rocks present in this unit include schists of the basal Nosib Group, marbles of the Ugab and Kudis Subgroups, schist, phyllite and amphibolite of the Chuos Formation and marble, schists and amphibolites of the Karibib and Kuiseb Formations, including the Matchless Amphibolite Belt.

Damaran meta-sediments have been intruded by granites in a broad zone between Otjiwarongo and Okahandja and the coast. The intrusion accompanied the mountain building process between 650 and 450 million years ago. Where individual granite bodies are too small to be shown on the Map, they were included in unit 11, “Metamorphic rocks, including quartzite and marble bands; with granitic intrusions”.

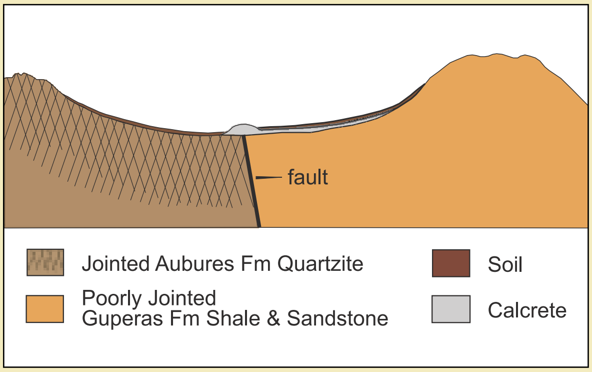
Unit 12, “Granite, gneiss, old volcanic rocks” finally includes a multitude of lithologies almost covering the entire geological history of Namibia. Vaalian rocks comprise the gneisses of the Epupa Complex and the intrusives of the Kunene Complex. Early Mokolian rocks include gneisses and meta-volcanics of the old metamorphic complexes, meta-volcanics of the Orange River Group, granites of the Vioolsdrif Suite, gneisses of the Elim Formation and meta-volcanics and gneisses of the Khoabendus Group. Middle to late Mokolian rocks of this unit are the meta-volcanics of the Rehoboth Sequence, the gneisses of the Namaqualand Metamorphic Complex, the meta-volcanics of the Sinclair Sequence, the granites of the Fransfontein Suite, as well as the younger granites, for example the Gamsberg Granite. The unit also comprises a range of syn- to post-tectonic granites which intruded Damaran sediments during the course of the Damaran Orogeny. Complex intrusions with ages of about 135 million years occur in a zone extending from the coast north of Swakopmund in a north-easterly direction. Some of them are extremely complex layered intrusions and contain rhyolite, granophyre, granite, syenite, foyaite, gabbro, dunite, pyroxenite and carbonatite. They are not related to any orogeny and interpretated as a result of a hot mantle plume, and have also been included in this unit.


Kevin Roberts

Etendeka Formation at Grootberg

Calcrete

The deposition of calcrete is affected primarily by climate and drainage. Other important and interacting factors are soil composition and thickness, topography, amount of dissolved Calcium and Magnesium carbonates in the water, time, stability of terrain surfaces, vegetation, and, in areas of thin soil cover, bedrock composition, structure and permeability. There are essentially two types of calcrete, pedogenic and non-pedogenic (groundwater) calcretes. In general, calcretes form in areas receiving a mean annual rainfall of less than 800 mm. Above 800 mm, all calcareous material is leached from the soil. In areas receiving between 550 and 800 mm, only calcrete nodules and calcareous soils form. Hardpan and boulder calcretes form where rainfall is less than 550 mm. Calcification develops readily in clayey, low-permeability soils, and less readily in sandy, permeable soils. Owing to the climatic conditions, calcretes can occur throughout Namibia.



Diagrammatic section showing pedogenic calcrete and a groundwater calcrete mound on a fault between poorly jointed Guperas shales, sandstones and highly jointed Aubures sandstone (Farm Aruab, Bethanie District).

The main components of calcretes are cryptocrystalline calcite and dolomite. Calcretes often cement fluvial gravels. Most exposed calcretes are fossil calcretes, but it is difficult to distinguish present-day calcretes from fossil calcretes formed under previous climatic conditions. Many calcretes are complex, may be of both pedogenic and non-pedogenic origin and formed by more than one phase of calcification.

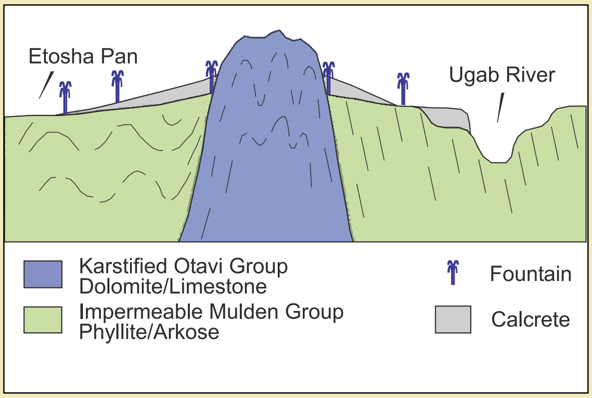
Pedogenic calcrete

Formation of pedogenic calcrete is part of the soil-forming process. Where shallow bedrock is present, the pedogenic calcrete forms at the contact between the bedrock and the overlying soil cover. In thick soil profiles or alluvial fans it generally forms at the lower limit of rain penetration. It is usually less than 1 m thick, but may reach up to 3 m in places, e.g. capping the Tsondab aeolian sandstone.

Many pedogenic calcretes are well structured consisting of individual calcrete nodules at the base, becoming more abundant and larger in size until coalescing to form a zone of honeycomb calcrete. The uppermost zone is a solid hardpan calcrete that is seldom more than 45 cm thick. Where a pedogenic calcrete is very thin, this three-unit structure is commonly absent and the calcrete may be almost entirely hardpan. The depth to the top of a pedogenic calcrete is generally about 20 cm in areas with less than 125 mm rainfall increasing to about 50 cm in areas with 750 mm of rainfall and more.

Critical to the development of pedogenic calcrete is the presence of groundwater or moisture with dissolved calcium carbonate within the zone of evaporation in surface soils or sands. Evaporation of this moisture precipitates the dissolved calcium carbonate as secondary limestone-pedogenic calcrete. Commonly in southern Namibia, the soil cover is only 5 to 30 cm thick. Although the underlying calcrete may be extensive, it is often only seen in incised stream profiles where the soil cover has been removed. Pedogenic calcretes form slowly and only below low-angle slopes. Each hardpan layer represents a period of stability of the land surface under which the hardpan formed.

Although pedogenic calcretes may be common in certain areas, they are not necessarily ubiquitous as the structure of the underlying bedrock and the porosity of the soil play an important role in preventing or enabling water to seep below the zone of evaporation. An example is provided from southern Namibia where sedimentary rocks of contrasting permeability are juxtaposed across a fault (as shown in the diagram). The Aubures sandstones are non-porous but highly jointed. Soil derived from the sandstones is sandy and sparse. In contrast, soils on the Guperas sediments from poorly jointed shales and sandstones produce a finer grained soil, which is generally less than 20 cm thick. There are no pedogenic calcretes on the Aubures Formation, yet they are common at the soil / bedrock contact on the Guperas Formation. This difference is ascribed to the contrasting joint density and hence permeability of the two underlying bedrock types. Pedogenic calcretes are not an indicator of groundwater at depth. Where they occur at the soil / bedrock interface they are rather an indicator of impervious bedrock.



Schematic section through karstified Otavi Group carbonate rocks and impervious Mulden Group phyllites and arkoses. Primary springs at the contact of the carbonates and phyllites are buried beneath their own calcrete and secondary springs emerge down slope where the thickness of the calcrete decreases.

Non-pedogenic or "groundwater" calcretes

Such calcretes are formed by fluvial action or by groundwater. They are deposited in the unsaturated zone above a shallow water table or below the water table where surface evaporation is extreme. On a small scale, seepages and evaporation at springs and along faults can form mounds of calcrete of limited lateral extent. However, calcretes formed by fluvial action or extensive near-surface flow of groundwater can exceed 100 m in thickness. In the fluvial process, the fluvial channel fill can become totally cemented by calcrete, e.g. the 100 m thick terraces on the north bank of the Ugab River west of Outjo or the gravels of the palaeo-Kuiseb River resting on top of the Tsondab aeolian sandstone.

However, far more spectacular, yet much less obvious, are the groundwater calcretes associated with springs along the contact between the Otavi Group dolomites and limestones and the Mulden Group arkoses and phyllites in northern Namibia. The Mulden rocks, particularly the phyllites, are largely impervious. Since the water table in the ridges is higher than that in the valleys, innumerable springs must have existed at the contact between the Otavi and Mulden rocks, even in Early Tertiary times. Upon evaporation of the spring water on surface, calcrete (and not tufa) was deposited at and downhill of the spring.

With time, the blanket of calcrete on the Mulden phyllites spread as the spring water seeped through the calcrete and emerged in places, particularly at the furthest edges of the calcrete. This calcrete blanket thickened as it spread, eventually burying the spring under its own calcrete.

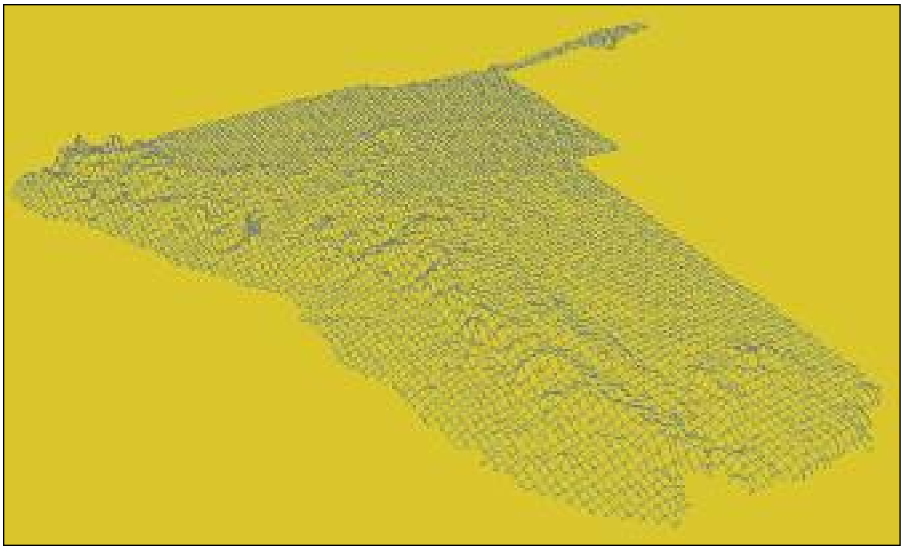
The process is bound to have been more complex than this relatively simplistic model, and it is probable that pedogenic processes were also involved.

This spring-generated groundwater calcrete is 128 m thick, 60 km north of Tsumeb, and 73 m thick, on the farm Braunfels, near Khorixas. Northwards into the Owambo Basin, as the distance from the Otavi carbonate rocks and the springs increases, the calcretes interfinger with clastic Kalahari sediments. Extensive karstification of the calcrete has enhanced its porosity and permeability. The subsurface contact springs still flow today, feeding the calcretes as well as the surface springs, e.g. the springs at the southern edge of the Etosha Pan (illustrated in this diagram).

Evidence in support of the above model is provided by the composition of the calcrete. Close to the basin margins and, hence, the source contact springs, the calcrete is a pure calcium carbonate. Further into the basin, the calcrete becomes more dolomitic. In the center of the basin, some of the boulder calcretes found at depth are actually dolocretes.

This change in composition of the calcrete with increasing distance from source is due to the greater solubility of dolomite. Calcite is therefore deposited close to the source and dolomite further away.

R McG MILLER



The landscape of Namibia

Geomorphology

The subdivision of Namibia into geomorphological units is based on its position on the edge of the African continent and under the influence of the cold Benguela Current. During the Cretaceous and the Tertiary, southern Africa completed its separation from the neighbouring parts of Gondwanaland. As a result of isostatic movements, the whole subcontinent underwent various stages of upliftment and the present interior was subjected to erosion. Such isostatic upliftment is most prominent along the edges of a continent, where erosion is most intense, and consequently, the Great Escarpment developed. Some of the highest peaks in Namibia occur along the Great Escarpment (see also the inset map "Altitude of ground surface" on the Map).

The coastal zone west of the Great Escarpment forms a 100 km-wide, low-lying strip characterised by extreme aridity and occupied by the Namib Desert. This desert, which is the world's most arid region, is underlain by sands of a proto-Namib phase which started to develop 35 million years ago. It stretches along the entire Atlantic coast and rises to a level of approximately 800 m at the foot of the Great Escarpment in the east. The Namib landscapes are quite diverse. They range from mountainous red dunes in the south-eastern part of the interior plains and flat-topped, steep sided inselbergs in the central region. Rocky desert as well as sand seas with various types of shifting and stable sand dunes occur. The Namib sand sea is cut sharply by the Kuiseb River east of Walvis Bay. The northern part of the Namib, known as the Skeleton Coast, displays bare dunes as well as stony and rocky plains. The Namib Desert is dissected by a number of rivers that rise in the Central Plateau but only carry water after good rains in their catchment areas. They form linear oases in the desert.

With differences in altitude of more than 1 000 m, the Great Escarpment marks the transition to the Central Plateau east of the desert. It is formed by mountain ranges or single mountains that are much higher than the Central Plateau. Between the northern and the southern parts there is an area that has been deeply eroded and where the ground rises gradually to the height of the Central Plateau. Plains and hills, as well as outstanding mountains such as Brandberg, Erongo and Spitzkoppe, characterise this area. The landscapes of the Central Plateau vary between very flat and mountainous areas at altitudes between 1000 and 2 000 m.

This mountainous plateau covers almost half of the country and is bordered in the east and north-east by the semi-arid Kalahari Basin. Two different main landscapes can be distinguished. The north-western highlands are characterised by broad valleys and inselbergs, while the south is a flat plateau dissected by deep valleys.

The Kalahari Sandveld stretches east of the Central Plateau and is formed by deep red or pale sands overlaying bedrock. This region is very flat and interrupted only by fossil valleys and dunes. A typical phenomenon in the Kalahari Sandveld are pans that are often covered by clay layers. The north-eastern Kavango and Caprivi Regions are characterised by a densely wooded bushland and comprise extensive wetland areas dominated by the Okavango, Zambezi and Kwando-Linyanti-Chobe river systems.

Climate

Namibia is an arid country that has a semi-desert on its eastern edge (Kalahari) and a desert on its western edge (Namib). The Namib Desert has a mean annual rainfall of less than 20 mm in places and mostly below 50 mm. The Kalahari stretches over three southern African countries, i.e. Namibia, Botswana and South Africa, and is largely a semi-desert with mean annual rainfall in the 150-350 mm range. According to the Köppen classification, Namibia as a whole is characterised as a dry climate. Three major types clearly emerge viz. cool deserts along the coast and south-western interior; warm deserts in the south-east and north-west; semi-desert steppe in the north and north-east. The mean annual rainfall for Namibia is about 270 mm and ranges from less than 20 mm in the Namib Desert to more than 700 mm at Katima Mulilo in the Caprivi Strip (see inset map "Rainfall and main catchments in Southern Africa" on the Hydrogeological Map). The distribution of land area receiving different categories of rainfall is as follows:

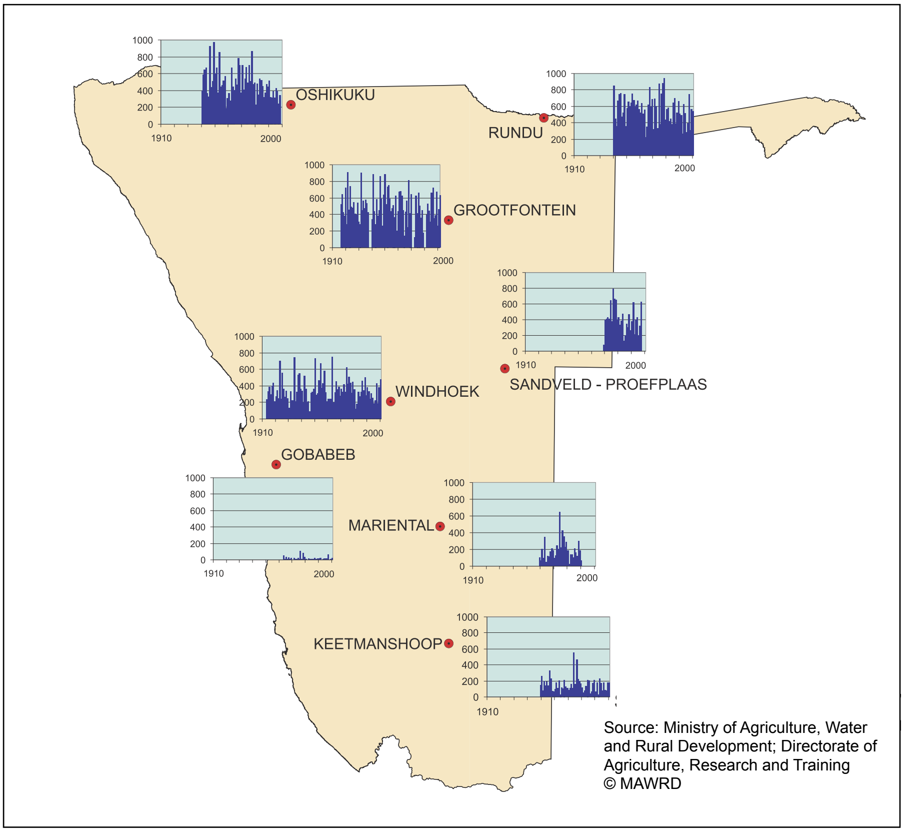
Rainfall	Percentage of land surface
less than 100 mm/a	22 %
100-300 mm/a	33 %
300-500 mm/a	37 %
more than 500 mm/a	8 %

However, the average figures may be misleading, since the annual rainfall is extremely variable in time and space, and variability generally increases towards the west and the south. Therefore, the variation of rainfall in time needs to be considered in addition to the long-term average aerial values. This variation is illustrated by the graph of annual rainfall for several climatic stations that have long-term records.

Namibia has a pastoral agriculture with crop production only being practised in the northern areas of the country where rainfall usually exceeds 500 mm.

Climate variations like droughts and to a lesser degree floods, have a major impact on the agriculture, and since a large proportion of the population still lives in rural areas, drought usually has devastating effects on commercial agricultural productivity and the rural poor.

The interior plateau of the country is characterised by



Source: Ministry of Agriculture, Water and Rural Development; Directorate of Agriculture, Research and Training
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Time series of annual rainfall at certain climatic stations in Namibia

an extremely high evaporation rate that far exceeds the average rainfall. Evaporation ranges between 2 400 mm/a along the coast and in the Caprivi, and more than 3 600 mm/a in the south-east (Aroab area of eastern Karas Region).

Distinct warm and cool seasons are distinguishable. The presence of a cold stable air mass along the coast and the altitude of the interior plateau result in temperatures lower than those expected for these latitudes. Temperature conditions along the coast can be described as moderately cool (15-20°C) while those of the interior as moderately warm (20-25°C). The temperature variation between summer and winter is more accentuated in the interior than the coast and these seasonal contrasts decrease northward. The warmest month differs from region to region with October being the hottest month in the north, in the central region it is December, and January in the south. The hottest temperatures occur in the south especially in the Orange River Basin (36 to > 40° C average daily maximum for the hottest month). Similarly, the coldest month varies from August along the coast to July in the rest of the country. The lowest temperatures occur in the eastern half of the central interior plateau (with night temperatures dropping below zero °C).

Along the coast the southerly and south-westerly winds dominate both in frequency (30 - 45 %) and strength (6 to more than 9 m/s), whereas the variable winds of the interior do not present a clear pattern. The warm, dry and dusty easterly winds that blow during late autumn and early winter, cause much discomfort along the coast as it is usually hot as well.

The cool air mass above the cold Atlantic sea water is overlain by a warmer, dry air mass, resulting in an almost permanent temperature inversion. Relative humidity is usually higher than 80 %. These conditions are ideal for the formation of fog and low stratus clouds. On average approximately 100 days are foggy, while there is a somewhat higher occurrence during winter along the central coast. This fog blanket is an important, and sometimes the sole source of moisture for the fauna and flora of the Namib Desert. In the desert research site of Gobabeb, new technologies are being tested to harvest the fog with large nets for water supply.

Hydrology

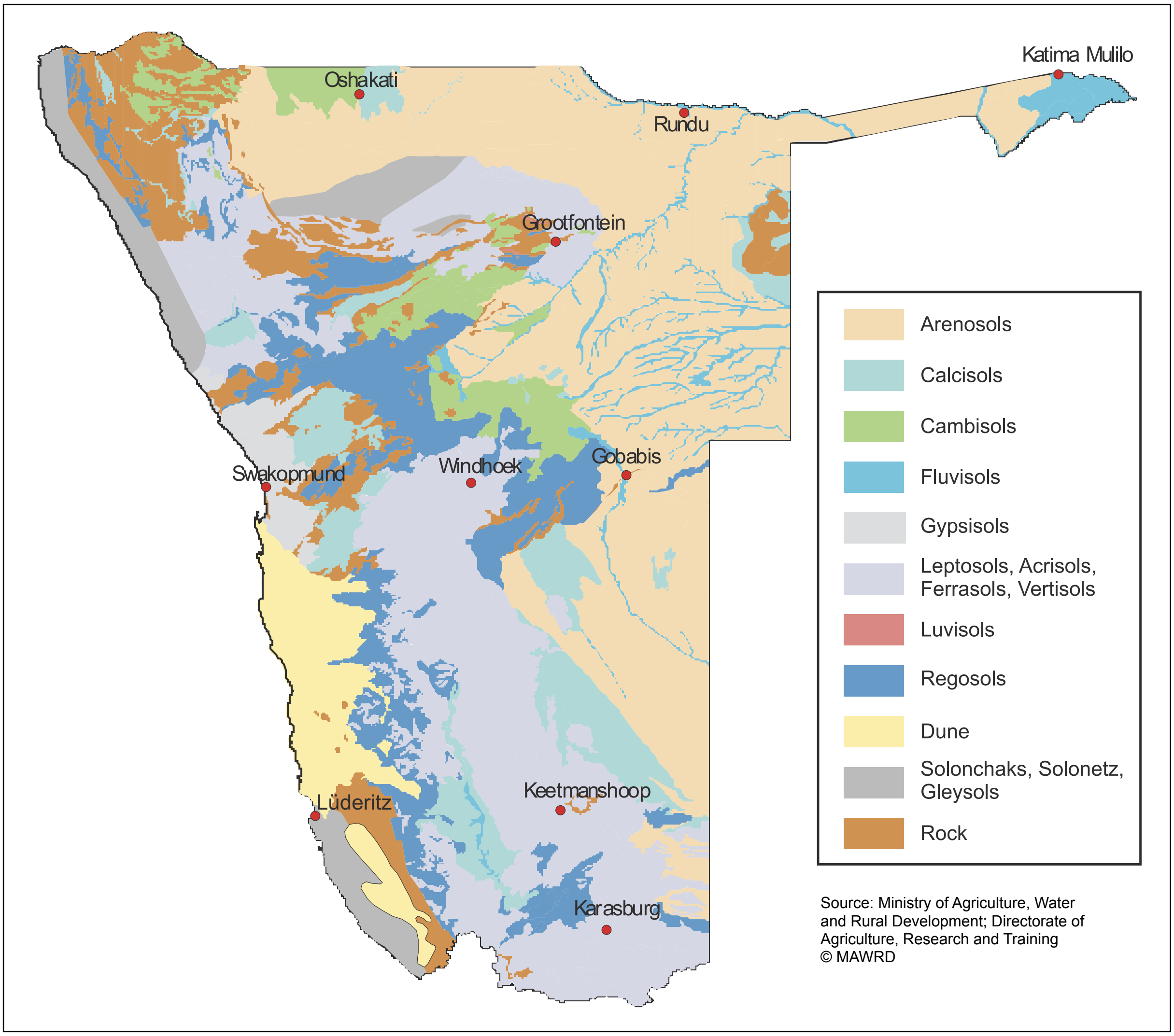
The hydrology of Namibia is characterised by the semi-arid to arid climate, and the very limited occurrence of surface waters. In fact, Namibia has no permanent rivers except for the border rivers Kunene, Okavango, Zambezi and Kwando - Linyanti - Chobe in the north and the Orange River in the south, all of which have their sources outside Namibia, and are shared with other countries (see inset map “Rainfall and main catchments in Southern Africa” and the table below). Some 23 % of the water used in Namibia is derived from these rivers, however, most of the country does not have access to this water due to the distances involved. Consequently, only 0.1 % of the total annual flow of these rivers is abstracted, in Namibia.

Percentage of Namibia’s land surface belonging to various catchment basins

Catchment Basin	Drainage System	Area (%)
Orange	Fish River Tributaries of the Orange River	14.7
Kunene	Tributaries of the Kunene River	1.8
Atlantic coast, combined catchments of westward flowing ephemeral rivers	Northern coast Southern Namib	22.1 10.2
Zambezi	Zambezi Kwando-Linyanti-Chobe	0.2 1.9
Okavango	Okavango River and Delta	23.9
Cuvelai / Etosha	Cuvelai / Etosha Pan	12.6
Southern Kalahari	Auob, Nossob, Olifants rivers	12.6

The rivers within Namibia are ephemeral rivers, flowing only for a short period after good rains in their catchment areas. Most of them flow towards the Atlantic Ocean, and form linear oases in the Namib Desert. Some limited drainage occurs towards the Kalahari Basin. Some large surface water storage dams have been built on these rivers to supply the major centres with water.

The percentage of the land area within the catchments of the large river systems within Namibia is given in the table above.



Source: Ministry of Agriculture, Water and Rural Development; Directorate of Agriculture, Research and Training
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Soils of Namibia

Soils

Extensive physical weathering, as well as erosion under arid and semi-arid conditions are the dominant soil forming processes throughout Namibia. Fluvial transportation is a prominent feature in the central highland areas associated with widespread sheet erosion. Over 70 % of Namibia's surface area can be classified as highly susceptible to erosion activities, making soil development very difficult in general.

Aeolian sedimentation processes are active in the Kalahari and Namib Deserts, where dunes and Hamada type landscapes prevail. Chemical weathering is hampered, mostly due to the lack of moisture. In the western Namib Desert, however, the breakdown of bedrock material is caused by salt contained in the coastal fog and derived from the marine environment. Tertiary and Quarternary deposits, such as dunes and flat sand plains, are morphological features dominant in the Kalahari and Namib Desert. Due to the low relief in these areas, calcareous deposits can be found in weakly eroded valleys (see Box on "Calcrete").

Soil forming processes, which are commonly found in the central highlands of Namibia, are mostly associated with saprolite weathering. Morphologically, such soil profiles are divided into a lower part with a more or less well preserved petrographic substructure of the bedrock material, and into an upper part, dominated mainly by disintegrated rock material. The saprolite material can reach up to several tens of metres in thickness and is dependent on the accompanying relief position, dominated by its erosion gradient and the geological substratum.

According to the FAO soil classification system, out of the 30 major reference soil groups the following do occur throughout Namibia: Acrisols, Arenosols, Calcisols, Cambisols, Ferralsols, Fluvisols, Gleysols, Gypsisols, Leptosols, Luvisols, Phaeozems, Regosols, Solonetz, Solonchaks and Vertisols. By far the most common soils are Regosols, Arenosols and Luvisols. Their main characteristic features include: high sand stratum, low nutrient content, low organic content, alkaline pH-conditions, typical for arid climate conditions with high evaporation rates, as well as high salinity. These soil groups in Namibia almost follow the major geomorphological and geological boundaries. The largest variety of different soil groups such as Cambisols, Luvisols, Acrisols, Regosols, Gleysols, Solonchaks and Solonetz, occurs within the coastal zone, the Namib and the Kalahari areas, whereas the central mountainous plateau, between the Namib and the Kalahari Basin, is dominated mainly by Acrisols, Cambisols and Luvisols.


Wynand du Plessis

Market near Oshikango

Along Namibia's permanent rivers, i.e. the Okavango, Zambezi, Kunene, Kwando-Linyanti-Chobe and the Orange rivers, Acrisols, Arenosols, Fluvisols, Regosols, Luvisols and Cambisols are common at various levels adjacent to the rivers on terraces and floodplains.

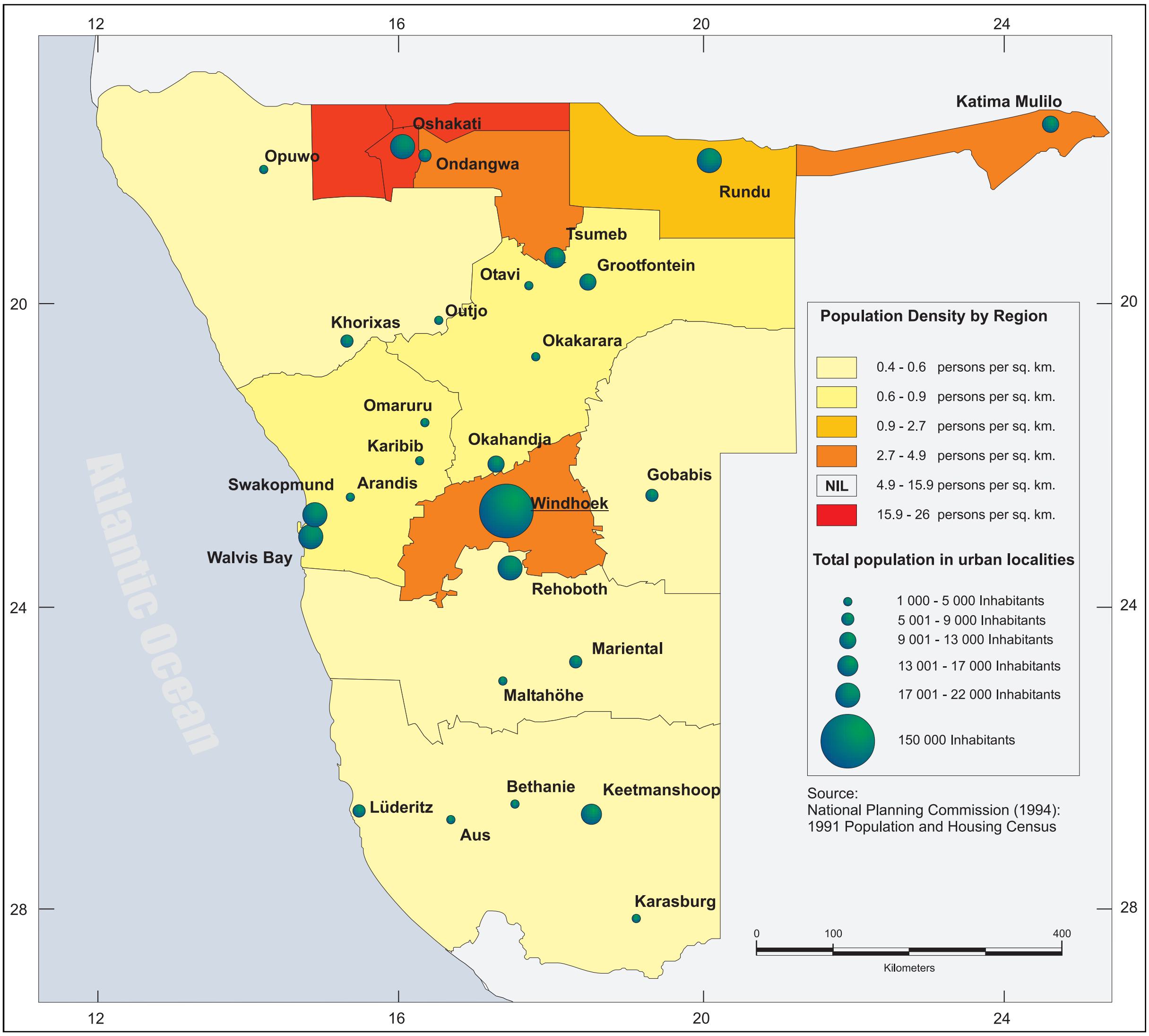
Vegetation

Three major vegetation zones, namely: deserts, savannas and woodlands, are dominant in Namibia. They are further classified into 14 subdivisons, which are determined according to major physiographical characteristics such as geology, topography and climate, and do follow their respective boundaries (after Giess, 1971, in Barnard, 1998). Woodlands and forest savanna make up the major types of woodland and cover the more humid north-eastern regions of Namibia. They also occur along all perennial rivers and the more common dry river beds, due to more favourable moisture conditions all year round. A variety of savanna type vegetation covers most of the country, of which highland, thornbush and mountain savannas are the most dominant ones to occur in the central highlands, and shrub and mopane savannas are to be found more frequently in the central southern parts, the Kalahari Sandveld and in the north-western parts of the country.

The desert as the remaining vegetation zone is divided into the northern, central and southern Namib Desert, which includes the succulent steppe vegetation zone influenced by winter rainfall. A more prominent semi-desert and savanna transition zone divides the Namib Desert from the savanna vegetation type along the Namib Escarpment.

Population

Namibia's current (2001) total population is estimated at approximately 1.8 million, and more than 70 % live in the central northern and north-eastern parts of the country (as shown on the map of "Distribution of Namibia's population"). With an average annual growth rate of between 2.5-3.5 %, the population is set to grow to 2.6 million by 2011 and 3.5 million by 2021. 70 % of the nation is younger than 30 years and 45 % younger than 15. Although Namibia ranks amongst the most scarcely populated countries worldwide, with an estimated density rate of 2 persons/km^2, only 1 % of its total area of 824 268 km^2 is suitable for seasonal and permanent crop production. Thus, the growing population puts increasing pressure on limited water and land



Source:
National Planning Commission (1994):
1991 Population and Housing Census

Distribution of Namibia's population

resources, health and education services, on the environment and on the adult working population. Rapid urbanisation and an ever increasing number of young people moving from rural areas to the few large settlements, towns and cities, will require well developed water management strategies to secure even basic living standards for Namibia's growing population.

Agriculture

Namibia's agriculture is dominated by livestock farming. Limited productive soils are common and these together with the low average rainfall of between 200-400 mm, as well as the extreme arid to semi-arid climatic and physiographic conditions, place severe limitations upon the country's agriculture. Cattle farming and crop production are mainly practised in the north of the country, where the rainfall exceeds 500 mm. Central Namibia, where mean rainfall figures vary between 200 and 400 mm, is suitable for livestock farming in general (cattle, sheep and goats), whereas the arid south-central and southern parts of the country, with a mean annual rainfall of between 50 and 300 mm, are only suitable for small stock farming. Major commercial irrigation farming takes place along the Orange River, at the Naute and Hardap Dams, and in the Stampriet, Tsumeb and Grootfontein districts.

To a lesser extent, cash crops are irrigated within the - so-called maize triangle between Grootfontein, Otavi and Tsumeb; along the Okavango and Zambezi rivers as well as close to many dry river beds throughout the country. Small-scale irrigation is also practised by various communities, mission stations and farm holdings, using fountain and borehole water to cultivate a variety of crops for own consumption. In 2000, irrigation from groundwater amounted to 30 Mm^3/a (see irrigation symbols on the Map), and there are plans to develop further irrigation from groundwater. However, this must be considered uneconomical and unsustainable for the scarce groundwater resources. Namibia still imports more than 80 % of its fruit and vegetable from South Africa, although the potential for increased irrigation from surface water resources exists. Prohibitive factors however, are the lack of management capacity and funding for the comparatively expensive investment of adequate, water-saving irrigation equipment and technology.

The important physical conditions of soils being utilised for irrigation include permeability, infiltration rate, field capacity, texture and water-holding capacity. Generally, soils used for crop irrigation in Namibia do have high sand and low fertility rates and low organic content, all of which requires proper soil management. Salinity, high evaporation rates and extreme erosion pose additional dangers.

Although water resources are well managed, severe droughts in the past have unfavourably influenced production figures for agricultural commodities. Agriculture's total contribution to Namibia's Gross Domestic Product (GDP) is between 9-10 % on average, of which 75-80 % can be attributed to extensive cattle farming activities, thus making livestock the major commodity within agriculture's total GDP contribution.

Mining, fisheries and tourism

Namibia's economy rests on three important pillars, namely mining, fisheries, and agriculture. Only limited beneficiation of raw materials is taking place, and Namibia depends heavily on imports of manufactured goods and technology, while it exports minerals, fish and beef.

Mining has long been the backbone of the Namibian economy and still today is the major contributor to GDP (12 %) and export revenues (40 %), as well as taxes paid into the Government coffers. Mining is also an important employer in Namibia. By far the most important mineral commodity is the diamond, mined in the south-western part of the country, as well as in unique offshore operations. So far, more than 70 million carats of diamonds have been produced in Namibia, the vast majority of which are of gemstone quality, placing the Namibian deposits amongst the best in the world.

Namibia is also one of the world's principal uranium producers, and the Rössing Uranium Mine operates the world's second largest open pit uranium mine near Swakopmund. Base metal mining has a long tradition in Namibia, with copper being the most important metal followed by lead and zinc. A gold mine operates near Karibib. The Namibian industrial minerals production comprises a range of commodities, including fluorite, salt and wollastonite. Namibia produces a range of dimension stones, including marble, granite and sodalite.

Commercial marine fisheries is an important sector of the Namibian economy. The Benguela Current off the Namibian coast is one of the most productive marine systems, second only to the Humbold current off South America. However, over-exploitation of pelagic fish between 1960 and 1980, when Namibia had no control of her marine areas, led to a collapse in the populations of several species. Stringent management after Independence has accounted for some recovery, and the contribution of fisheries to GDP has risen to 10 %. Like mining, fisheries is an important employer.

Tourism is an important growth sector in the Namibian economy. The country boasts a variety of unique landscapes and splendid wildlife. The vast open spaces in Namibia's sparsely populated areas allow the experience of solitude and direct contact with nature, especially appreciated by travellers from the overcrowded centres of Europe and elsewhere in the world. Coupled with the well developed infrastructure and abundant accommodation, from camp sites to 5 star hotels, this makes the country a prime tourist destination. Namibia is linked to Europe by regular flights, and via Johannesburg, South Africa, to all major centres in the world.

In this context, eco-tourism plays an ever increasing role. This gives the country a good opportunity to develop its community-based tourism ventures, which already brings a lot of benefit for the local people in remote areas, who otherwise have little access to economic activities other than subsistence agriculture. In turn, it gives the tourist the opportunity to become acquainted with the Namibian way of life.

Tourism currently directly contributes 3 % to GDP, however indirect contributions also occur. This figure represents a growth of 100 % in the last decade, and is certainly set to increase even further, as tourism develops in Namibia.

GIC SCHNEIDER, MB SCHNEIDER, AL DU PISANI

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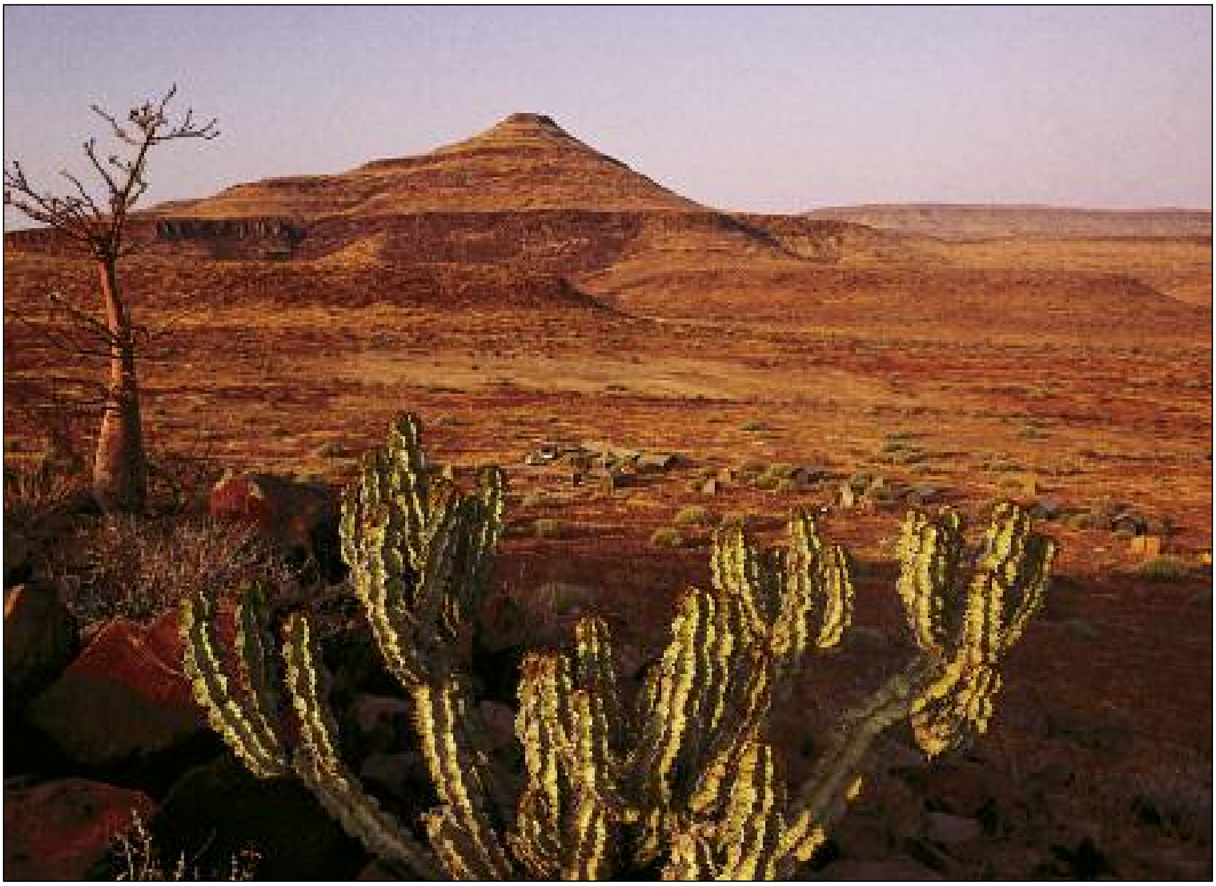


Kevin Roberts

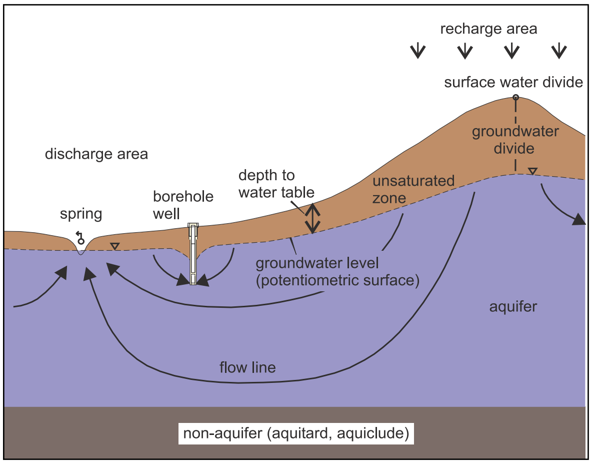
Etendeka Mountain Camp in a scenic area dependent on very limited groundwater supplies

Essentials of Groundwater

Wynand du Plessis

This chapter describes some of the general features of the hydrogeological environments in which groundwater occurs. This should help the reader to understand the chapters that provide a more detailed account of the geology related to water bearing formations, the occurrence of groundwater, and the water supply potential of the aquifers.

The occurrence of groundwater is closely associated with the rock formations making up the crust of the earth. When these three-dimensional bodies of rock contain underground water, they are called "aquifers". These aquifers have unique properties dependent on internal and external factors controlling their size, capacity, the groundwater flow regime, the quality of the groundwater and their long-term sustainable safe yield potential.



A groundwater flow system with its input (recharge) and output (discharge)

Groundwater potential

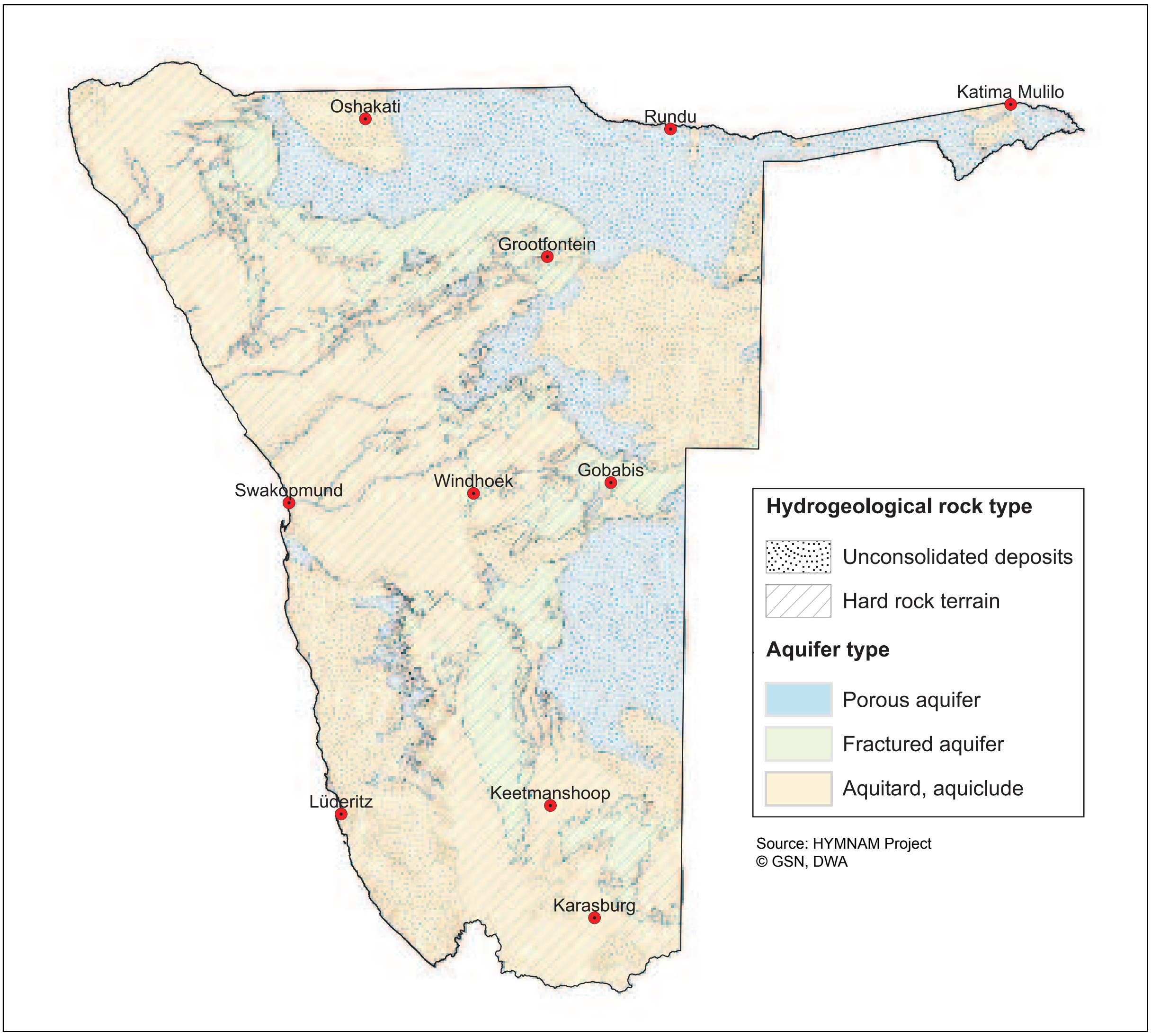
The potential of an aquifer to yield a certain quantity of water with a certain chemical quality at a certain rate depends on its size, the volume of water that can be stored, (called the storage capacity) the chemical composition of the rocks that the water comes into contact with, the volume of water moving through the aquifer system per time unit (called the flux), the water available to replenish or recharge the aquifer and the water flowing out of the system (called the discharge). The recharge is normally from rainfall and runoff seeping into the aquifer while the discharge can be natural or man-made. Natural discharge takes place at springs or seeps. Man-made discharge is caused by collecting water from wells that have been dug by hand or by pumping the water out through boreholes drilled deep into an aquifer.

The nature of the rocks underground determines if they are water bearing, the quality of the accumulated water, and how much groundwater there is. The storage capacity of an aquifer in a rock formation is determined by the percentage of open spaces in the rock that can collect water in comparison to the total volume of the solid rock. This is called the porosity of the aquifer.

In sand, the porosity may be as high as 20 % because the number of spaces between the sand grains are high. The unconsolidated or poorly consolidated sand and gravel layers in sedimentary rocks generally form excellent aquifers, but the stored volume of groundwater depends on the thickness of the rock saturated with water. The quantity of groundwater stored in fractured aquifers is usually much less, because the space is confined to cracks, fissures and fractures in an otherwise solid mass of rock.

An important variation in fractured hard rock aquifers are the carbonaceous rocks in which the fractures have been enlarged by the chemical solution of the rock in the water percolating through the aquifer system. These aquifers are called karstified aquifers and the aquifers in the Grootfontein-Tsumeb-Otavi Mountain Land are typical examples.

The rate at which water can flow through an aquifer is called the permeability of the aquifer. In some deposits such as clay, silt and fine sand the porosity may be high, but the permeability is low because the capillary forces hold the water confined in the rock mass. Aquifers with low permeability are called aquitards or aquicludes. In such cases it is difficult or impossible to abstract the groundwater economically because a large number of large diameter boreholes must be drilled and installed to obtain enough



Source: HYMNAM Project
© GSN, DWA

The principal aquifer formations of Namibia and their representation on the Hydrogeological Map

water to meet the required demand.

Certain favourable geological features enhance the use of aquifers with low permeability. When fault zones or valleys following zones of crustal weakness cut through aquifers with low permeability, the water collects over a large area and can be abstracted at an exceptionally high rate by boreholes drilled into these favourable water collecting structures.

As shown in the map above, the following types of aquifers are widespread in Namibia:

- Porous aquifers
- Fractured aquifers
- Aquitards or aquicludes

The rate at which groundwater can be abstracted from an aquifer is determined by the porosity and the permeability. The quantity of groundwater that can be abstracted over time is determined by the rate at which the water can be abstracted and the volume of water that is available for abstraction is determined by the storage capacity of the aquifer. The long-term sustainable safe yield from an aquifer also depends on the recharge of the water abstracted or discharged from an aquifer.

From this it is clear that a number of hydrogeological factors must be considered when looking at the groundwater potential and good structural geological knowledge is imperative to site successful boreholes, especially in hard rock aquifers (see Box on "Borehole design").

Technical and economical aspects are also important. These are, for example, the depth that a borehole must be drilled into the aquifer, the type of pumping installation required, the depth at which the pumpset must be installed, the rate of abstraction possible from the aquifer, the pumping head to elevate the water to the surface and how much water can be abstracted on a sustainable basis.

Tapping and abstracting the groundwater

To use groundwater usually requires investments to drill a borehole and to install a pumpset to abstract the water. Springs are certainly the lowest cost option. Where groundwater naturally appears on the surface, it can be harnessed almost for free, as a gift of nature. However, to meet growing demand and to provide clean spring water, investments are required to fence the springs, or deepen the pond and capture the discharge in a reservoir. The potential value of springs as a source of low cost water supply has given rise to a new database in which information on spring locations, discharge yield and flow regime (perennial or seasonal), water quality, technical installations and water use are kept. This database must be continuously updated and expanded, since springs are ecologically and hydrogeologically very important sensitive points, that can provide integrated information about the groundwater systems that feed them. When a spring ceases to flow, the consequences can be dramatic. People and animals lose a reliable source of drinking water supply and an important aquatic habitat is lost. For the scientist, this is a clear indication of alarm that something has happened to the groundwater flow system feeding the spring, e.g. the balance between recharge and spring discharge has been disturbed by drought, climate change, or by high groundwater abstraction in the vicinity of the spring (see Box on "Groundwater-fed wetlands").

Where groundwater levels are close to the surface, shallow wells can be dug by hand. The isoline of 20 metres depth to the groundwater table is shown on the Map, indicating where groundwater levels are regionally shallow. The isoline of 100 m is also shown, to delineate areas where the groundwater is very deep. Everywhere else, the depth of the water table varies widely, depending on the topography and geology, but good site-specific predictions can be obtained from professional hydrogeologists. Groundwater resources lying deeper underground are tapped by boreholes or wells. Boreholes have a designed installation and are built to use groundwater on a long-term basis (see Box on "Borehole design").

Since the groundwater table generally follows the surface topography, it is clear that groundwater is found at more shallow depths in valleys while higher up in the hills and mountains the groundwater is much deeper. However, under certain favourable conditions (in a confined aquifer) groundwater at depth, might be under pressure and come up close to the surface, even in a deep well. This is often encountered in a multi-layered sedimentary basin where the aquifer is sealed at the top by low permeable beds, and its pressure relates to the higher lying recharge areas at the margin of the basin or in hard rock areas where confined groundwater from a deep fracture zone is struck. In some areas of Namibia, e.g. in the Stampriet Basin, the Maltahöhe- or the Oshivelo area, groundwater tapped in deep wells need not be pumped because the water flows out freely from the borehole due to the high pressure head, thus forming an artesian well. Artesian and sub-artesian zones are delimited on the Hydrogeological Map.

Sustainable use of groundwater

It is a clear objective of water resource management in Namibia to use the groundwater resources on a long-term sustainable basis, without causing environmental damage. This implies that the full storage potential of a groundwater system is not utilised, but merely the long-term annual recharge determined from water balance calculations.

According to the overall water balance of Namibia, it is estimated that on average only 2 % of the annual rainfall

Importance and vulnerability of groundwater-fed wetlands

Groundwater supports many of Namibia's wetlands. Perennial rivers only occur along the northern and southern borders of the country and other surface water is seasonal or restricted to impoundments.

The riparian zones of ephemeral rivercourses, sinkhole lakes, springs, seeps and waterholes are all examples of wetlands fed by groundwater. Such wetlands provide resources to wildlife, livestock and people throughout Namibia and have a significance far greater than their water production alone. They are oases of resources, providing a habitat, shelter and food in otherwise dry surroundings for a variety of plants and animals. Many of these are specially adapted organisms not found anywhere else, such as the Otjikoto tilapia, *Tilapia guinasana*, that occurs only in sinkhole lakes and the blind cave catfish, *Clarias cavernicola*, found only in Aigamas Cave in the Karst area, both endemic to Namibia.

Springs are often ancient in human terms and all those in Namibia are sites of archaeological interest and early settlement.


Shirley Bethune

Gemsbokbron, Skeleton Coast Park

Threats to groundwater-fed wetlands

Springs and riparian zones are often threatened by human use. As natural focal points in the arid landscape, promising water, shade and food, they attract human activity. Because they are small, spring-fed wetlands are vulnerable to activities that can reduce their natural resource value and decrease biodiversity. Some activities can destroy a wetland or cause the extinction of endemic species.

Lowering of groundwater levels through over-abstraction

Permanent springs can become temporary and riparian trees and floodplain vegetation die. The size of wetlands can be reduced and biodiversity lost.

Pollution

Diesel pump leaks, faeces and insecticides easily pollute springs and pools because of the small total volume and flow. Grazing and trampling by livestock can quickly destroy the habitat of small wetlands and riparian zones.

Alterations to springs

Dams, capping, blasting and drains are often attempted to "improve" springs. These activities can reduce the wetland area, stop the water flow, kill aquatic life and cut off access for dependent wildlife.

Developments

Tourist lodges, houses, dams or mines near springs scare wildlife away. Pesticides to control water-borne disease vectors and even lights can eliminate local populations of useful aquatic invertebrates.

Impoundments

Building dams on ephemeral rivers can cut off natural floods and reduce groundwater recharge to downstream aquifers and floodplains on which riparian vegetation, people, livestock and wildlife depend, e.g. Oanob Dam and the downstream Rehoboth camelthorn woodland.

Tourism

People often camp at spring pools in remote areas. This may reduce access for wildlife and cause pollution and disturbance. Tourists may unwittingly bath, and even wash their vehicles, in springs causing pollution. Although one group may only spend a single night at a spring, it is likely that other groups will soon follow.

K ROBERTS

creates surface runoff, and only 1 % contributes to groundwater recharge. However, this does not take regional surface differences into consideration. Certain rock types exposed at surface are impermeable and no water can infiltrate, but others are capable of absorbing and storing virtually all excess rainfall which is not lost to direct evaporation or evapotranspiration. In these areas almost no surface water drainage system develops. Predominant examples are the Otavi Mountain Land with its karstic aquifers and the area covered by calcrete or dune-sand in the Stampriet Artesian Basin.

Recharge to groundwater systems is difficult to measure. It depends on a complex variety of factors, such as rainfall intensity, soil conditions and soil moisture, the slope or gradient of the surface topography, vegetation cover and land use, depth of the water table and, of course, the characteristics of the underlying aquifer. This implies that the same rainfall event can produce different amounts of recharge, not only for different hydrogeological environments (sand cover, sandstone, granite, calcrete or dolomite terrains), but also whether it falls on a plain or in the mountains. Less water infiltrates during the growing season when vegetation cover is denser and plants take up water for growth and transpiration.

Stable and radioactive isotopes in atmospheric water, soils and groundwater are often used to determine the age of groundwater and its recharge. The safest way to compute the recharge, however, is by hydrogeological modelling of the water budget of a groundwater flow system, provided its size and aquifer parameters as well as the cumulative discharge abstracted from the system are sufficiently known. The aquifer parameters, such as permeability, transmissivity and storage coefficient can be analysed from pumping tests of boreholes. The abstraction from boreholes must be continuously monitored. The correct design, construction and installation of boreholes is crucial to successful groundwater abstraction (see Box on “Borehole design”).

In general, there is a strong correlation between rainfall and recharge. This is evident in comparisons of rainfall records and the groundwater levels, monitored in many places in Namibia, by the DWA, NamWater and private land owners.

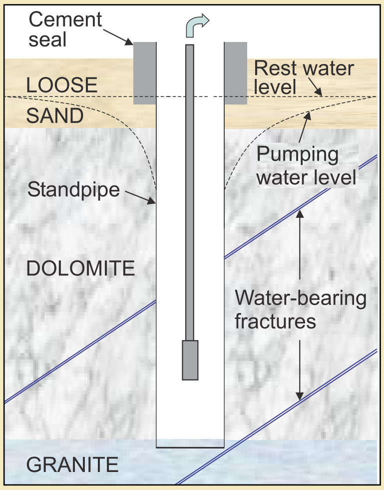
In a semi-arid to arid country like Namibia, it is of crucial importance that groundwater abstraction volumes are known

Borehole design

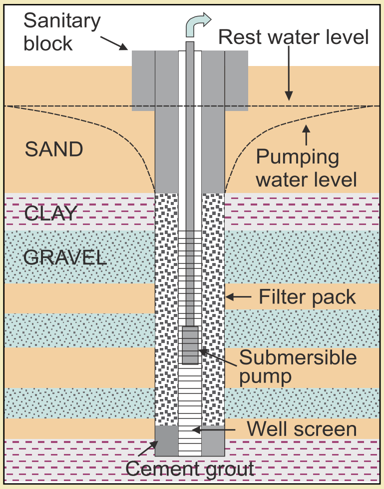
A borehole is a hydraulic structure that permits the abstraction of water from an underground water bearing formation. Since boreholes are drilled into the ground and some of the equipment to abstract the groundwater is located underground, the capital investment in the installation is only partially visible. As boreholes are rather expensive infrastructures, they must be properly designed, constructed and installed to ensure a long service life and the most economic operation. If this is not done properly it will result in an inefficient water yield and high pumping costs. In the long run this will be a very expensive mistake. The development of a successful borehole is achieved through the joint efforts of hydrogeologists, drillers and engineers. The hydrogeologist sites the borehole, supervises the drilling and designs the borehole once it has been drilled. The driller uses the most appropriate drilling technique and materials for a particular hydrogeological environment. The engineer takes advantage of the hydraulic conditions of the borehole to design the equipment to abstract the water in the most economical way and to distribute the water to the users.

Various drilling methods have been developed to cope with different geological conditions ranging from hard rock environments such as granite or dolomite, to unconsolidated sediments such as alluvial sands or gravels. Borehole construction usually comprises several activities of which the drilling of the borehole is the most basic. This is followed by the installation of casing, well screens and the placing of filter packs as necessary. Then the borehole is developed to ensure that the water is free of sand and that the sustainable maximum yield is obtained. Grouting can also be done to provide a sanitary seal to protect the water in the borehole from contamination. Private boreholes are usually drilled only until enough water has been struck and further cost is avoided. However, such boreholes can only tap part of the aquifer potential. Preferably, they should intersect the whole water bearing formation. In production boreholes for large scale abstraction the correct aquifer parameters are scientifically determined, yet in practice even such boreholes are often "incomplete" due to technical constraints such as the thickness or depth of the geological units, the high drilling cost to drill a deep borehole and the energy cost to abstract water from great depths. In other words, the shallower the water, the more economical it is to abstract.

When boreholes are drilled in fractured rock environments, water is struck when a water bearing rock fracture is intercepted. The borehole will yield little or no water if such fractures are missed. Fractured aquifers are mostly confined, so that a sudden rise in the water level occurs when the water bearing fracture has been struck. In Namibia, these boreholes are usually drilled with the "down-the-hole-hammer-rotary-percussion" method.



Borehole design for fractured aquifers



Borehole design for porous aquifers

The borehole wall in rock environments is usually stable, and only a standpipe is set up in the upper parts of the borehole to prevent loose soil entering the borehole.

Special drilling methods are required to drill in unconsolidated sediments. The most common method used in Namibia is the mud rotary method. Chemicals are used to stabilise the borehole wall to prevent it from collapsing. Mud is pumped down the borehole during drilling to ensure that the pressure inside the borehole is higher than that of the surrounding formation. After the well screen and filter pack are installed, the mud must be removed.

The filter pack allows the formation to be hydraulically connected to the borehole but prevents it from entering the borehole through the well screen. A sanitary seal is required at the surface, and the borehole must be grouted at the bottom to prevent the filter pack or aquifer material entering the well during pumping. Unconsolidated formations are often unconfined so that the depth at which groundwater is encountered and the depth to the water level are the same. This distance from the ground surface to the water level in the borehole is called the depth to groundwater.

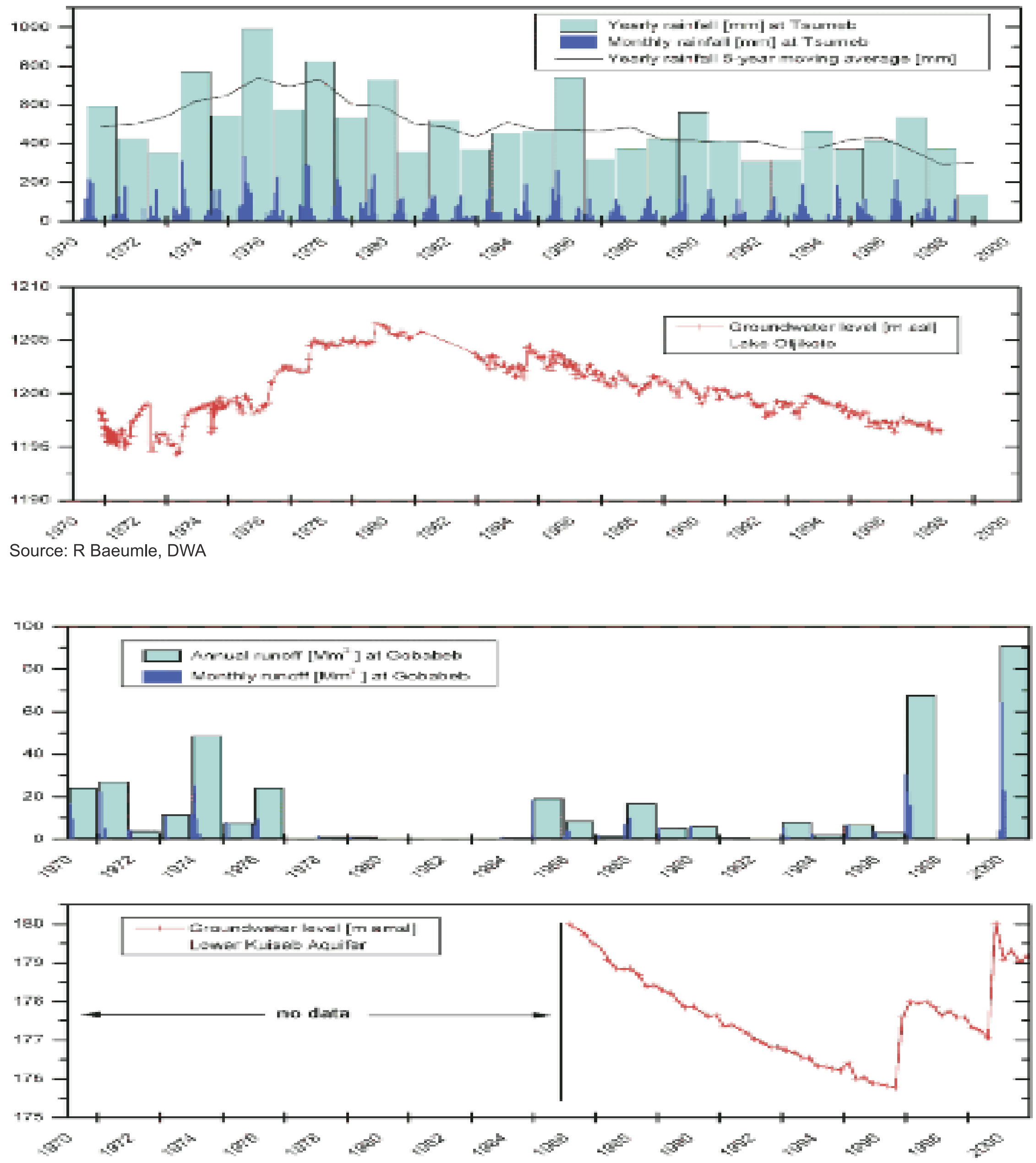
The level at which the water stands in a borehole before water is pumped out is called the rest water level. When the abstraction of water is in progress, the water table is lowered and this is called the pumping water level. When the groundwater is under pressure in a confined aquifer, the water level rises in the borehole after drilling and when the groundwater flows out naturally at the ground surface, it is referred to as artesian. In some cases, e.g. in the Stampriet Artesian Basin or in the Oshivelo Artesian Aquifer, the artesian water level may be several metres higher than ground level.

The borehole yield is the volume of water per time unit that is discharged from a borehole, either by pumping or when it flows out freely under artesian conditions. In Namibia, the rate of flow is commonly measured in cubic metres per hour.

A VAN WYK

Jürgen Kirchner

African IAEA training course at artesian borehole in Stampriet



Source: R Baeumle, DWA

Source: C Wessels, NamWater

Correlation between rainfall and water level, in different groundwater regions in Namibia

and measured, to avoid over-abstraction and environmental damage. This requires that groundwater users are listed, receive a license to use the groundwater and that they are obliged to measure their abstraction and report it. This, together with independent records from a groundwater monitoring programme, ensures that aquifers are used in a balanced and sustainable manner.

Lowering of water levels alone is not clear proof of groundwater over-abstraction, but can be a warning sign. In properly managed groundwater systems, abstraction from storage and declining water levels may be permissible to sustain the water demand during drier periods, provided it causes no lasting environmental damage (see Box on “Vulnerability of groundwater-fed wetlands”). The system can then be recharged in future wetter periods and the water levels can recover completely.

Another clever option to manage water resources in Namibia is to transform surface water into groundwater. Open water surfaces, e.g. lakes or dams, are extremely prone to evaporation and this loss of water may be as high as 70 %. Therefore, techniques to store water underground to protect it from evaporation and to enhance recharge have been developed and used in Namibia since the beginning of the century. Simple options are the construction of sand storage dams and ground weirs in river beds. All these traditional techniques of harvesting surface water and groundwater were to ensure wise water use. This is thoroughly reviewed by Lau & Stern (1990).

A larger, more sophisticated artificial groundwater recharge scheme has been built in the lower reaches of the Omaruru River. Here, the Omaruru Delta (Omdel) groundwater scheme is recharged from an impoundment with a storage volume of 41.3 million m^3 when full. Surface runoff collects in the dam upstream from the aquifer, where once the silt has settled out, the water is then slowly released into infiltration basins downstream of the dam. Boreholes are used to abstract this enhanced, recharged groundwater from the Omaruru Delta Aquifer. This innovative scheme forms part of the water supply to the central coastal area.

Vulnerability and protection

Namibia is the most arid country in southern Africa, making the surface and groundwater resources all the more important and vulnerable to pollution and over-utilisation. To guard against this, a vulnerability assessment must be carried out before any development of the resources. The findings and mitigating measures must be applied in the management strategy to ensure the protection of the resources. Although groundwater resources are, to a certain extent, naturally protected underground, they too are vulnerable to certain pollutants and hazards. The quantitative aspect of vulnerability, e.g. over-abstraction, mining and drying up groundwater systems, is covered on the previous page.

The quality of a groundwater system might be endangered or destroyed by inappropriate or no protection of the "hidden groundwater treasure". There are numerous examples world-wide, where precious groundwater resources that are invaluable assets for the water supply to both the environment and future generations, have been damaged or made useless by pollution resulting from inappropriate agricultural and industrial land-use activities above or upstream of important groundwater systems.

Despite a good environmental policy protecting biodiversity and ecosystem functioning in Namibia and successful environmental assessment programmes, a deficit remains regarding the protection of known and potential groundwater resources. The potential hazard for contamination of groundwater systems from private, municipal and industrial activities, particularly the discharge of wastewater effluents, the use of landfills and refuse dumps, must be assessed (see Box on "Groundwater and waste disposal").

The same applies for more diffuse contamination from intensive agricultural activities. Similarly the threats to groundwater-fed wetlands must be assessed and taken into consideration in any future development of these as a potential low-cost water supply alternative (see Box on "Importance and vulnerabiliy of groundwater-fed wetlands").

G CHRISTELIS, P HEYNS, W STRUCKMEIER

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Groundwater and waste disposal

Waste disposal by landfill is the most common means of disposing of municipal refuse, ash, garbage, building rubble as well as sludge from municipal and industrial wastewater treatment facilities. Radioactive, toxic and hazardous waste has also been buried. Water that runs over uncovered waste or infiltrates into buried waste can cause compounds to leach from the solid waste. The resultant liquid is called the leachate. Leachate from waste disposal can contain very high concentrations of both organic and inorganic compounds. It can move as surface runoff during the rainy season into drinking water supplies such as dams, lakes and rivers, or downward from a waste disposal site into underlying groundwater systems and cause contamination.

When leachate mixes with water, it forms a plume that spreads in the direction of the groundwater flow. With distance from the source of the plume, the concentration decreases due to dilution, dispersion and retardation processes. The volume of leachate produced is a function of the amount of water that percolates through the refuse. Waste disposal management must be designed to minimise the formation of leachate and to control the leakage from a waste disposal site.

Waste disposal in Namibia has been, and still is, a neighbourhood dump on the edge of a town, village or mining settlement. All types of waste have been, and still are, being dumped in any readily available hole or depression such as valleys, sand and gravel quarries, and marginal lowlands. Many of the sites have been located near residential areas and water supply zones, resulting in high pollution and health risks. During the planning of most of the waste disposal sites still in use, no ground investigations were conducted and neither were pollution risks and environmental protection taken adequately into consideration.

However, current state of the art practices for selecting a suitable waste disposal site, call for careful evaluation of climatic, environmental and geological data. A desk study is undertaken to gather pertinent data sets, and these are used in the detailed site investigations, data evaluation and risk assessment, taking into consideration social, economic and political interactions. Field studies are then undertaken for individual sites and detailed data collected on the environmental and ground models, the amount and type of waste, and major industrial activities. Potential contaminants from the waste generated are evaluated with respect to their impact on fauna and flora as well as their potential for surface and groundwater contamination.

Environmental geological mapping is undertaken to obtain detailed qualitative ground data required for a safe, sound and economic site design. The pathways of potential contaminants such as faults, fractures, gullies and ephemeral rivers are delineated to determine risks to surface and groundwater. This delineation of possible pathways is done through field geomorphological mapping, hydrological and geotechnical evaluations. Laboratory studies on the mineral composition of individual lithologies and geotechnical analyses of the soil and rock samples are also carried out.

Tsumeb municipal waste disposal sites

Tsumeb has three municipal solid waste disposal sites all situated to the south-west of the town. All are located on top of heavily fractured and partially karstified dolomite rock outcrops forming a major aquifer throughout the Otavi Mountain Land. Tsumeb receives a variable rainfall averaging 550 to 600 mm/a and given the high infiltration rates typical for this Karst

Sindila Mwiya

Tsumeb open dumping sites

Tsumeb open dumping sites: burning waste in a heavily fractured old quarry

Sindila Mwiya

area, groundwater recharge is relatively high, too. Thus, all three municipal solid waste disposal sites in Tsumeb are at risk of large-scale groundwater contamination.

Windhoek municipal solid waste disposal sites

The Windhoek municipal solid waste disposal sites are located in and around the city. There are seven sites, of which six are for garden and building rubble (class three sites) and Kupferberg is the only class one site capable of handling hazardous waste. The rainfall for the Windhoek area is highly variable but averages around 400 mm a year. The geology of the area consists of mainly schist with quartzite. None of these sites are located on the quartzite with a good groundwater potential. Nevertheless, at most of the sites there is a high risk of contaminating surface water resources. The main risk pathways are river valleys and gullies through which contaminated runoff from the open dumping sites can reach drinking water sources such as dams.

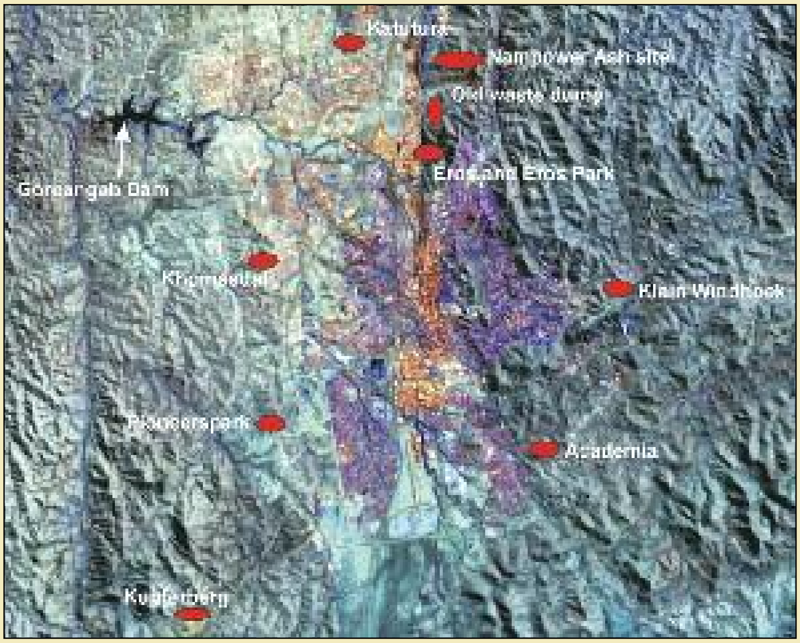
Gobabis municipal waste disposal sites

The Gobabis waste disposal site is located to the south-west of the town. The area receives around 300 - 400 mm of rain per annum. The geology consists of variable schists with quartzite. The open dumping area can influence water quality, because the wind can transport contaminants from the open dumping area to where these can then be transported further by surface runoff to open water supplies such as dams.

Gobabis open dumping site

Landsat Thematic Mapper Image

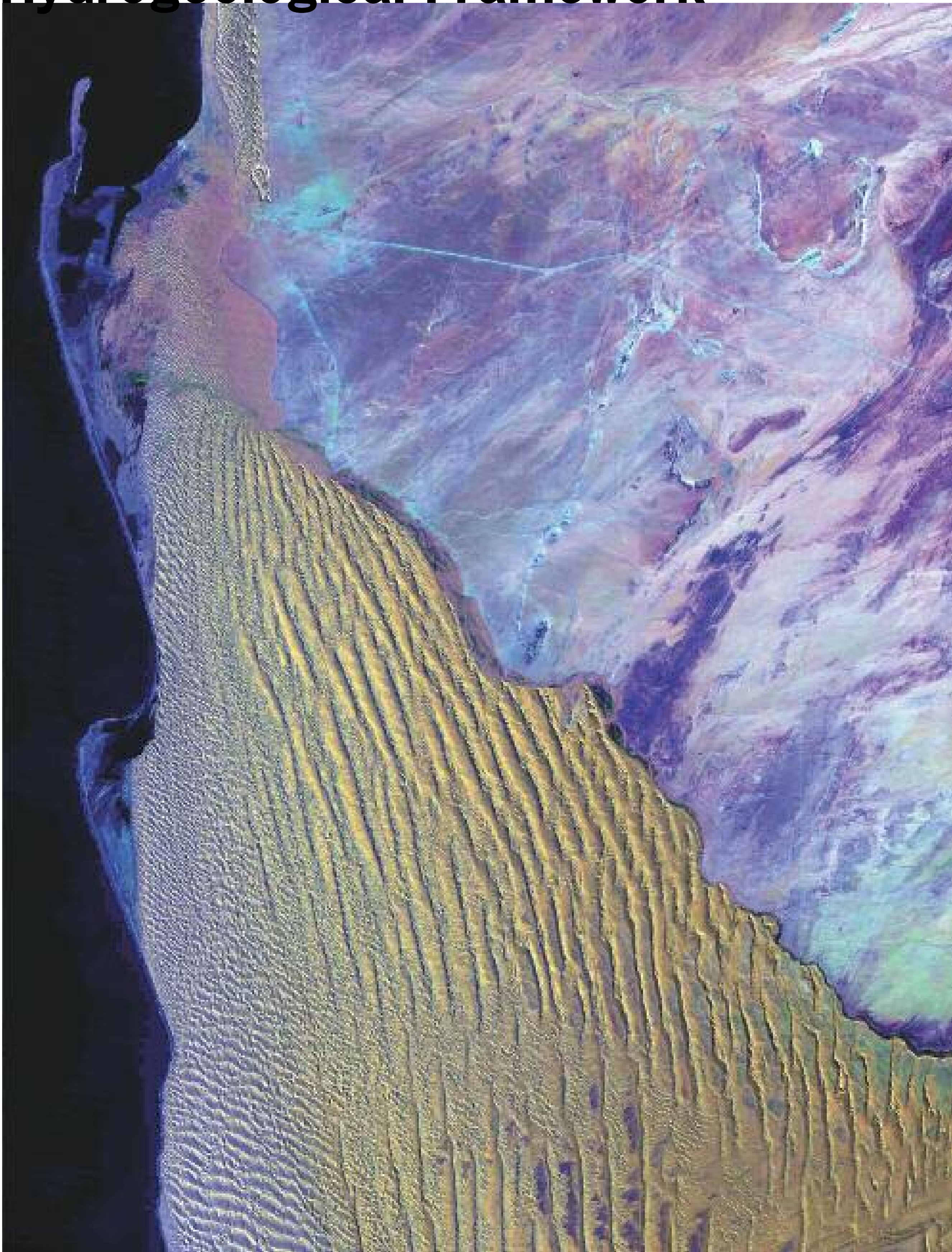
Municipal waste disposal and other potential sources of water contamination such as septic tanks, fuel storage tanks at service stations and mines will always be of great concern. Understanding the interactions of climate, environment and geology is vital for selecting suitable waste disposal sites that minimise the risk of contamination. The research and development of knowledge-based systems in waste disposal technology is an important tool that will ensure the protection of ground- and surface waters and limit the risks and impacts of pollution. S MWIYA



Windhoek's waste disposal sites

Landsat Thematic Mapper (TM) band 1, 2 and 4 (false colour composite)

Hydrogeological Framework



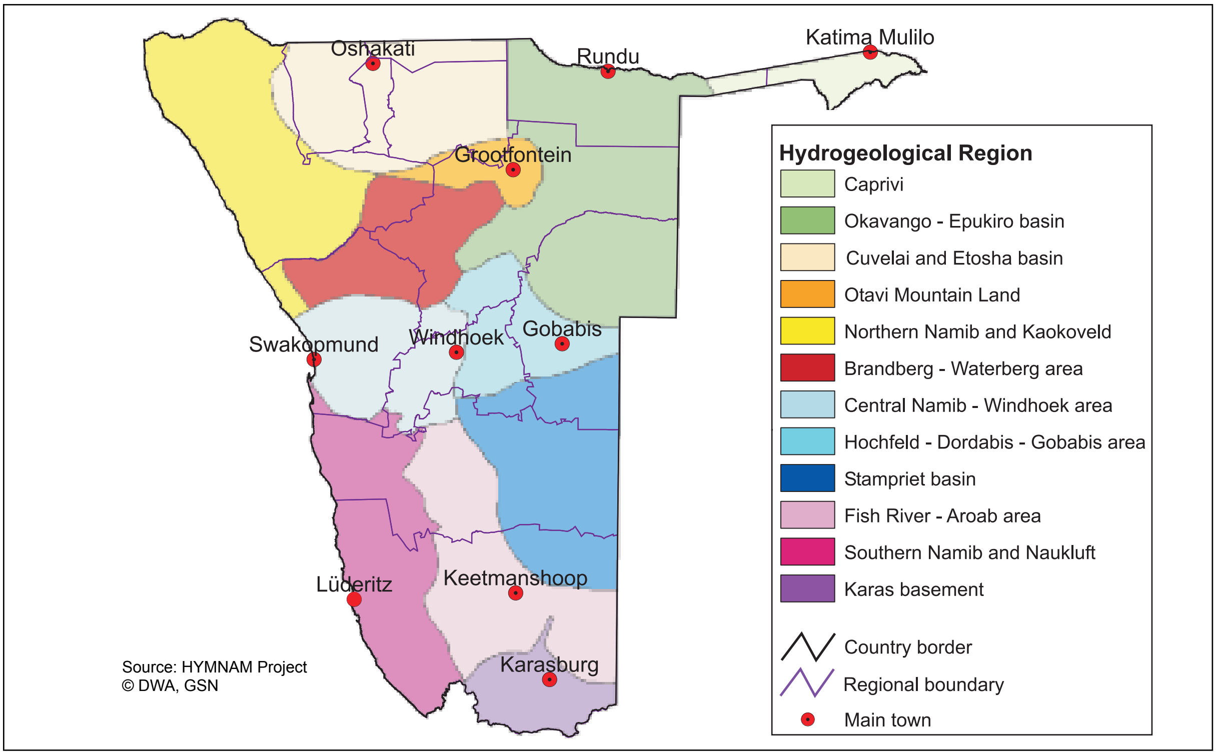
Landsat Thematic Mapper Image

Groundwater basins and their hydrogeological features

The country has been divided into twelve hydrogeological regions based mainly on geological structure and groundwater flow. To avoid confusion with political regions, these units are called "groundwater basins". Their boundaries were chosen to encompass areas of similar geology and hydrogeology. This chapter describes the geological structures, the lithological bodies and their hydrogeological properties, the groundwater quality as well as the use of the groundwater resources. For the well-known groundwater supply schemes run by NamWater, numbers referred to in Annex 1 are added in brackets.

The sub-chapters have been written by groundwater experts familiar with the various regions. They integrate the information on geology, drilling, geophysical investigations and hydrogeology in the broader sense taking into consideration aspects of groundwater quantity and quality. The information provided in this chapter summarises the state of knowledge on the groundwater situation and complements the Hydrogeological Map, which, to remain legible, portrays only the most pertinent hydrogeological features and detail. To know more, the reader is referred to the groundwater and environment related literature, reports and data kept in the files of the main co-operating partners for this Hydrogeological Map Project, i.e. the Department of Water Affairs (DWA); the Geological Survey of Namibia (GSN); and the Namibia Water Corporation Ltd. (NamWater).

The technical and professional terms used are explained in the attached glossary. According to the Namibian classification system, groundwater quality ranges from Group A to D. This classification system based on the concentration of total dissolved solids (TDS) is explained in Annex 4. Areas in which poor quality groundwater occurs are shown by orange hatching on the Map.



Source: HYMNAM Project
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Groundwater basins and hydrogeological regions in Namibia

Caprivi Strip

The hydrogeological region of the Caprivi Strip encompasses the Namibian territory east of the Okavango River. This flat area is characterised by rather uniform geological conditions at the surface, dense vegetation, the highest rainfall and the lowest evaporation rates in the country.

Sediments of the Kalahari Sequence and more recent deposits overlie almost the entire Caprivi area. An isopach map of the Kalahari deposits shows that it thickens from the western end of the Caprivi Strip (where it is absent in the basement outcrops in the Okavango River south of Bagani) towards the Kwando and Linyanti rivers reaching a thickness of up to 300 m. From the Kwando River towards the north-east the Kalahari, cover thins out again to less than 30 m.

Outcrops of underlying rocks are scarce and the geology is only known from a few exploration boreholes. The subsurface geology of the Western Caprivi is dominated by the Damara Sequence consisting of quartzitic sandstone and dolomites, partly covered by volcanic rocks in the central western part. Mainly volcanic rocks underlie the Kalahari throughout the Eastern Caprivi although sandstones of the Etjo Formation are present in some parts.

Hydrogeology

Groundwater in the Caprivi is mainly tapped from the Kalahari Sequence, which displays variable groundwater properties over short distances. It forms a porous aquifer, indicated in blue shades on the main Map. Fractured aquifers are absent in the region. Variable yields from 0 to more than 20 m^3/h are recorded. Although the lithology intersected during drilling is important, the success of a borehole is less dependent on the siting technique than on drilling and well construction methods. In many boreholes, low yields and clogging are due to poor borehole design and construction.

Owing to the generally shallow water tables, boreholes drilled for water production, tap only the upper Kalahari layers in which the following six lithological classifications are recognised: Alluvium and lacustrine deposits, duricrusts (calcrete, silcrete, ferricrete), sand, sandstone, marl, basal conglomerate and gravel. Recent alluvium of fluvial origin usually occurs in the floodplains of the Kwando-Linyanti-Chobe system. Coarse pebbly gravels within the upper 30 m in the central area between Katima Mulilo and Ngoma, probably represent paleo-Zambezi deposits of Pleistocene age.

Surficial sand of aeolian origin consisting of reworked Kalahari sediments covers almost the entire land surface of Eastern Caprivi. The transition from the so-called Kalahari sand to the older, underlying sandstone is gradual and often not clearly distinguished in borehole samples. Sandstones represent the major lithology in the Kalahari Sequence, however, the term must be used with caution. During drilling operations, every gradation from unconsolidated sand to dense quartzite was observed. In less consolidated material, clay is often present, to the extent that the sandstone grades into sandy clay. Where more consolidated, the sandstone contains either a siliceous or calcareous matrix.


Gabi Schneider

Floodplain of the Zambezi River in Eastern Caprivi


Kevin Roberts

Rock outcrops in the Zambezi River at Wenela

Lacustrine deposits are found in an extensive network of linear pans lying east-north-easterly. These are seen as analogues of ancient, larger lake systems within the assumed basin structure underlying a large part of Eastern Caprivi. Marls generally occur as thin horizons, up to several metres thick, and probably represent rather isolated lenses within the succession of sandstones.

Groundwater use and quality

Although geophysical techniques are less important for siting high yielding boreholes in the Caprivi, they help trace groundwater quality. Generally, it is the chemical composition rather than the yield potential that restricts groundwater use. The water quality is highly variable throughout the region. Iron is a major concern, causing a high percentage of water points to be classified as Group D water. This can be effectively overcome through the use of low-technology iron removal systems. Good quality water is generally found up to 5-20 km from the rivers, which recharge the aquifers. The water quality often deteriorates rapidly away from the rivers and with increasing depth to groundwater. Recharge in the central part is low with most of the water derived from precipitation. The velocity of the regional groundwater flow is extremely low.

The Caprivi has been divided into five hydrogeological provinces displaying similar and consistent hydrogeological characteristics:

The Caprivi-West Province stretches between the Okavango and the Kwando rivers excluding a 20 km-wide zone along these rivers. The water quality is usually good, groundwater can be located easily and is available in sufficient quantities. The depth to water level deepens towards the west and is mostly too deep for handpump installations. The military base at Omega (73) has a water supply scheme based on this aquifer. The thick Kalahari sediments obtain fairly regular recharge from rainfall and sustain a wellfield of medium potential and Group B water quality.

Shirley Bethune

After a hot day in the Caprivi, when Lake Liambezi still had water

The Kwando Province consists of a 20 km-wide zone along the Kwando River from the Angolan border to the Samudono village. This province is recharged from the Kwando River and borehole yields are mostly high. The water quality is generally Group A, but rising iron concentrations can result in B-D Group quality.

The Linyanti Province is a 20 km-wide zone north of the Linyanti River, stretching from Samudono in the south-west to Lake Liambezi in the north-east. Water quality is generally poor, with elevated concentrations of sulphate and total dissolved solids. High iron concentrations are also common, especially near Lake Liambezi. At Chinchimane (20), close to the Linyanti River, a water supply scheme was built, because the intermittent flow in the river threatened the surface water supply. In this area a layer of better quality water is sandwiched between two layers containing poor quality water. The upper aquifer has Group B-C water, but the lower aquifer (deeper than 50 m) is saline. The sediments consist of fine sand, silt and clay, that often contain organic matter, causing anaerobic conditions, an unpleasant smell, and deposits of "black mud" in the boreholes. The pumping rate of the wells is limited to 2-4 m^3/h to prevent the inflow of saline water from the lower aquifer.

The Northern Province joins the Kwando Province and the Linyanti Province east and north up to a line running from Lake Liambezi to the Zambian border. Water quality ranges from Group A to D, with problems caused mainly by sodium, sulphate and chloride, while iron concentrations are generally low. Water levels are the deepest in the northern part of this province, making it difficult to use conventional handpumps. Most of the groundwater development is alongside the B 8 Golden Highway. The rest of the area is not well developed and little water quality information is available.

Gabi Schneider

Village in the Eastern Caprivi

The Zambezi-Chobe Province is situated between the Zambezi and Chobe rivers, bordered to the west by the Linyanti and Northern Provinces. Water quality is generally good, but elevated iron concentrations may produce Group B to D water. Water levels are mostly shallow making the installation of handpumps possible. Groundwater information for this province is limited to a few points in the west. At the groundwater supply scheme of Bukalo (19), the Kalahari sediments are very fine-grained making it difficult to establish high-yielding boreholes. Large diameter wells made of concrete rings were tried as an alternative with limited success.

P BOTHA

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Okavango-Epukiro Basin

The Okavango-Epukiro groundwater region is located in a huge flat area in north-eastern Namibia encompassing the entire Kavango Region as well as the eastern parts of Otjozondjupa and northern Omaheke.

Most of the area belongs to the Okavango drainage system, including the dormant, usually dry riverbeds draining east towards the central Kalahari. The area generally receives comparatively good rainfall and is covered by thornbush savanna.

Geology

The Okavango-Epukiro Basin lies at the margin of the much larger Kalahari Basin, which extends far across the Namibian border. The bedrock that underlies this huge sand-filled basin consists of various rock types. Outcrops of carbonate and quartzite of the Damara Sequence are present in the area of Gam and Tsumkwe. The carbonate rocks, which are correlated with the dolomites in the Otavi-Tsumeb area, form the Aha Hills 60 km north of Gam. Further south of Gam, drainage courses such as the Epukiro and the Eiseb omiramba have exposed the underlying bedrock composed of marble, mica schist, quartzite and amphibolite. Dolerite dyke and sill intrusions occur in the area, but outcrops are very scarce and can usually only be detected by geophysical methods. Some volcanic rocks are exposed in the Okavango River at Rundu and between Mukwe and Bagani, at Dobe Pan and in the upper reaches of the Otjosondjo Omuramba.

The Kalahari Sequence forms a blanket of unconsolidated to semi-consolidated sand covering most of the area. Specialists divide the Kalahari layers here into three main units. The uppermost consists mostly of unconsolidated windblown sand and sand deposited under fluvial conditions. The middle part is predominantly fluvial sand with minor aeolian deposits. The basal layer is as yet poorly understood and consists of conglomeratic, red clayey sand with carbonate cement. The thickness of the Kalahari layers is lowest (less than 50 m) along the Botswanan border and increases towards the middle reaches of the Omatako Omuramba and further to the north-west.

Several prominent geological structures are found in north-eastern Namibia. The south-east trending Gam lineament is a major fault with a downward displacement of 200 m on the southern side. The Eiseb graben extends between the Eiseb and Elandslaagte omiramba and contains 250 m thick sand layers. Towards Otjiwarongo the north-east trending Waterberg thrust brought about an abnormal thickening of Kalahari sediments. Recent drilling in the Goblenz area penetrated more than 460 m of Kalahari deposits.

Hydrogeology

Groundwater within the area is hosted in two distinct aquifer systems, Kalahari aquifers and fractured bedrock aquifers. These two aquifer types are treated separately here as they have different characteristics. Kalahari aquifers hold water in intergranular pore spaces, whereas water in fractured aquifers is held in cracks and fractures in otherwise impermeable strata. Kalahari aquifers are common in the north-eastern Otjozondjupa and Kavango regions. In northern Omaheke, the Kalahari is generally non-saturated, but groundwater may be present in fractures in the underlying bedrock. Adjacent to the Botswana border, from Gam in the south to the Kaudom Park in the north, bedrock formations crop out and groundwater occurs in fractured aquifers.

Drilling success rates, defined as the percentage of boreholes yielding more than 1 m^3/h, are commonly 100 % in areas of known Kalahari aquifers, whilst the lowest success rates, of less than 25 %, are common for fractured aquifers beneath thick unsaturated Kalahari layers. The most difficult areas to find groundwater are north and east of Otjinene.

Groundwater in the Kalahari aquifers is relatively easy to locate throughout most of the north-western and central northern Tsumkwe district and the Kavango Region. The sediments form an almost continuous permeable layer from which generally low yields can be abstracted via boreholes. Factors determining yield include, variations in permeability, saturated thickness (often limited by drilling depth) and borehole or well diameter and design. Shallow aquifers with water levels above 20 m receive good recharge either directly from rainfall or indirectly from ephemeral runoff.

Deeper aquifers are recharged from the Kalahari basin margins and underlying fractured aquifers. Groundwater level elevation (piezometric surface) and hydrochemical evidence suggest significant recharge from the Otavi Group dolomites in the Tsumeb-Grootfontein area, e.g. to the Goblenz area. Replenishment of the deeper aquifers far

Wynand du Plessis

Natural rainwater pool with water lilies in the Khaudum Game Park away from the basin margins is, however, unlikely to be significant.

A depiction of depth to groundwater level provides a useful indication of the depth of drilling required. The north-eastern areas, north of Gam and east of Rundu, adjacent to the Okavango River and along the Omatako Omuramba are characterised by water levels less than 30 m below ground. Water levels are also relatively shallow in the south-west adjacent to the margin of the Kalahari and along the upper reaches of the Epukiro and Otjozondjo omiramba. Here, groundwater for domestic and livestock use is supplied to villages and rural communities including farms. Boreholes closer to the centre of the basin, tap deeper water as the depth to groundwater gradually increases to more than 100 m.

Boreholes intersecting fractured bedrock aquifers may show higher yields than boreholes tapping Kalahari aquifers. However, groundwater exploration in fractured aquifers is more difficult, often relying on the application of geophysical and remote sensing data. Exploration for groundwater in fractures from 30 to more than 100 m below unsaturated Kalahari deposits in northern Omaheke has met with low success, despite the application of sophisticated airborne and surface geophysical techniques. This area is shaded in brown on the Hydrogeological Map, indicating a low yield potential.

Drilling along features such as the Gam Lineament has proven successful, with yields over 3 m^3/h being common. In areas of thin or absent Kalahari cover, as in the Epukiro Omuramba in the vicinity of Post 3, lithological contacts and faults are discernible and borehole success rates are moderate. Here, water quality is variable and saline groundwater can be expected in some boreholes. In the bedrock areas adjacent to the Botswanan border water levels tend to be shallow although groundwater levels can vary up to 10 m in places between dry and wet seasons.

Groundwater use and quality

Drilling techniques and borehole construction practices have changed over the years, and recent drilling results show a general improvement in yields in some Kalahari aquifers. In most cases high yields are not required for small communities. Boreholes are thus drilled to the depth at which sufficient yields are achieved. It is probable that in many areas where low yields were reported in the past, deeper drilling and appropriate borehole construction might have resulted in higher yields. Similarly, in other areas, deeper intersection of fractured aquifers can also achieve a marked increase in borehole yields.

In the Kavango Region, boreholes and dug-wells are concentrated, as are the people, along the Okavango River, the Omatako valley and the main roads from Grootfontein to Rundu and Tsumkwe. The main criteria have apparently been physical access and communication rather than constraints imposed by groundwater availability.

The following water supply schemes in the Okavango-Epukiro Basin make use of groundwater. The western-most scheme close to the Okavango River is Mpunguvlei (59) where, in spite of the name, no “vlei” (marsh) or surface water can be found. Groundwater occurs at considerable depth in the Kalahari sediments, is of insufficient quantity and Group D quality due to high fluoride concentrations.

Further to the east, a number of missions, hospitals and schools form the core of villages on the banks of the Okavango River. Most of these are supplied with groundwater, because the river water may be infected with bilharzia. The yield of boreholes in the fine-grained Kalahari layers along the Okavango River is generally low. The groundwater flow direction is chiefly towards the river and there is hardly any recharge of river water into the Kalahari aquifer. Groundwater in the Kalahari along the banks of the river often shows poor quality due to its iron and manganese content, which exceeds the limits for drinking water. The water quality is mainly determined by the Kalahari aquifer, in which the groundwater travels over long distances. When the Okavango River recharges the aquifer during floods, this inflow of river water can locally improve the groundwater quality.

Due to problems experienced with corrosion of steel casings and clogging of borehole screens with organic matter and precipitates, borehole schemes have been abandoned at places where large volumes of water were needed. For instance, the Linus Shashipapo and Kandjimi Murangi schools now receive treated river water.

The eleven schemes still operating along the Okavango River are from west to east: Nkurenkuru (63), Kahenge (39), Tondoro (97), Rupara (89), Buinja (17), Mupini (60), Kayengona (46), a relatively new water scheme with higher than average pumping rates, Sambiu (90), Nyangana mission (64), where replacement boreholes with plastic casing were drilled, Andara mission (4) and Bagani school (11). The more dispersed distribution of water points and settlements in the north-eastern Otjozondjupa and northern Omaheke regions, is a consequence of poor groundwater availability. The schemes at Rooidaghek (87) and Runduhek/Mururani gate (88) are used for veterinary border posts on the roads from Grootfontein to Tsumkwe and Rundu. The Kalahari sediments in this area are up to 350 m thick, the aquifers are semi-confined and have low groundwater potential. Similar conditions apply to the police station at Maroelaboom (57) and the now defunct police station at Tsintsabis (99). The settlement of Tsintsabis is located close to the boundary with the Cuvelai Basin. Here the Kalahari layers have very low yields and the water demand has increased to twice the sustainable yield.

Dryland agriculture and settlements close to the Okavango River

Four small water schemes are found further east towards Tsumkwe: Aasvoëlnes (1), Mangetti Duin (56), M'kata (58) and Omatako (69). They supply settlements established at former army camps from 145-200 m deep boreholes tapping low-yielding Kalahari aquifers.

Tsumkwe (100), the centre of the former Bushmanland is surrounded by pans and vleis. The area has a shallow water table of 1-6 m with groundwater occurring in Kalahari calcrete and calcareous sand. The thin Kalahari sediments are underlain by basalt of the Kalkrand Formation. The water quality is variable. Two production boreholes have Group A water and the other two Group C water due to high fluoride concentrations. The yield of the scheme is insufficient to meet the town's demand and extensions are planned for the near future.

Bedrock outcrop areas such as the Aha Hills near Tsumkwe and Gam are extremely vulnerable to groundwater contamination. This is due to enhanced recharge potential from shallower water levels, lack of soil cover and the dominance of fracture flow within these systems.

The water supply scheme of Goblenz (33) is located southeast of Grootfontein in an area where the rock formations of the Karst region dip steeply to the south and disappear under more than 460 m of Kalahari sediments. The town was supplied with groundwater from deep boreholes with insufficient yields until it was linked to the Hereroland pipeline system in the late 1980s. However, the groundwater resources were recently re-evaluated and high-yielding boreholes established to supply Goblenz with groundwater in future. The area is considered to have high potential indicated in dark blue on the Map. The long-term sustainable yield of the Goblenz Aquifer has been assessed to be 2.7 Mm^3/a, maintained by diffuse groundwater flow from the dolomite recharge area to the Kalahari sediment trough. Along the flow path, the radiocarbon age of the groundwater increases from a few decades to 3 000-10 000 years at Goblenz.

The Otjituuo Reserve is supplied with 0.7 Mm^3/a of dolomite groundwater from two strong boreholes near Berg Aukas, east of Grootfontein.

The Okakarara treatment plant, as part of the Eastern National Water Carrier (ENWC), receives dolomite groundwater from Kombat Mine in the Otavi Mountains via the Grootfontein-Omatako Canal. It has a capacity of between 3.2 to 3.5 Mm^3/a. During the past four years (1998-2001), an average of 2.3 Mm^3/a was pumped from the Kombat Mine water into the canal and treated at Okakarara. The treated water can be piped to Otjituuo, as depicted in the Map.

Okondjatu (68), a school village in the Otjinene district, obtains water from a wellfield approximately 10 km north, where a low-yielding fractured aquifer is present in Damara Sequence meta-sediments beneath thick Kalahari layers.

A group of old boreholes installed with wind pumps and delivering Group C quality water was replaced with new wells showing better Group B water quality. Otjinene (81) is a town on the Eiseb Omuramba in the Omaheke Region. Kalahari sediments of about 80 m thickness overlie metasediments of the Damara Sequence. Production boreholes were sited using geophysics to locate fractures in the bedrock, which promised higher yields. The water quality varies between boreholes from Group A to C. The scheme currently comprises 11 boreholes and the sustainable yield is sufficient to meet the demand.

In the sandveld area of north-eastern Otjozondjupa and northern Omaheke, groundwater resources in the Kalahari beds and underlying bedrock are considered to require only minimal protection, as groundwater vulnerability here is low or negligible. Significant depth to the water table and a reasonable attenuation capability of the Kalahari sands account for this.

In terms of water supply, the former "Epukiro Reserve" is a notorious problem area. The Kalahari sediments in the area around Omawewozonjanda or Epukiro Post 3 (23) and Okovimburu/Post 10 (24) contain no groundwater. Water is only found in the underlying Damara rocks, mainly in thin marble bands, on contact zones or fractured quartzite and schist. Finding these targets requires powerful geophysical techniques to ensure at least a moderate success rate for drilling. Forty boreholes were drilled at Post 3, of which only 6 can be used as production wells with yields of 1-4 m^3/h. Some boreholes are located on fractures crossing the omuramba, but these aquifers usually show a higher salinity. The borehole yields at Post 10 are low, but the water quality is better than at Post 3. West of Epukiro, the Plessisplaas (85) police station is supplied from a low-yielding aquifer in thin Kalahari layers.

The Rietfontein (86) water scheme supplies a number of farming communities along the Rietfontein River near the Botswanan border. The Kalahari cover is almost absent in this area exposing rocks of the Kamtsas Formation (Damara Sequence). The borehole yields are low to moderate and insufficient to meet the rising demand. Overabstraction has caused a change in water quality from Group B to C.

A SIMMONDS

Cuvelai - Etosha Basin

The Cuvelai-Etosha groundwater Basin is the Namibian part of the Cuvelai River catchment. Perennial tributaries occur only in Angola while in the Namibian part of the basin, the oshanas flow only in the rainy season. These oshanas are shallow, often vegetated, poorly defined but are interconnected flood channels and pans through which surface water flows slowly or may form pools depending on the intensity of the floods (“efundja”). Water is also supplied to Namibian villages and towns in the Cuvelai Basin from Calueque Dam, just north of the Angolan border, via an extensive system of canals and pipelines.

The Cuvelai Basin is bordered in the south and west by the surface water divide running from Otavi to Outjo, Kamanjab, Otjovasandu, Otjondeka, Opuwo and Ruacana. In the east, the boundary is formed by a faint groundwater divide running north from Tsintsabis almost at 18° E longitude, while in the north it is the international border between Angola and Namibia. The hydrogeological Cuvelai Basin thus comprises the Omusati, Oshana, Ohangwena, and Oshikoto regions and parts of the Kunene Region. Most of the land surface of the basin is very flat dipping from some 1 150 m above sea level (asl) in the north-east to 1 080 m asl in the Etosha Pan, which is the largest pan in Namibia. All drainage is thus in the direction of the Etosha Pan.

The Cuvelai Basin is the most densely populated area of Namibia and most of the inhabitants live in rural communities dependent on agriculture. Rainfall decreases from 600 mm/a in the north-east to 300 mm/a in the west. In the same direction, potential evaporation increases from 2 700 to 3 000 mm/a. The relatively high and reliable rainfall allows dryland crop farming in addition to cattle and small stock farming. Light industries and businesses have been established in towns like Oshakati and Ondangwa.

Geology

The Cuvelai Basin, including Etosha Pan, is part of the much larger Kalahari Basin covering parts of Angola, Namibia, Zambia, Botswana and South Africa. It contains a very thick series of rocks of various ages. The basin floor consists of gneissic and granitic basement. Outcrops of this occur in the Kamanjab Inlier along the south-western rim of the basin (Fransfontein Granitic Suite and Khoabendus Group, 2 700 to 1700 Ma). Up to 8 000 m of sedimentary rocks of the Nosib, Otavi and Mulden groups of the late-Proterozoic Damara Sequence overlie this. Carbonatic rocks of the Otavi Group are found on the surface in the mountain ridges south and west of the basin. The Damara Sequence is followed by 360 m of Karoo Sequence rocks ranging from Lower Permian to Jurassic (300 -130 Ma) and up to 600 m of semi- to unconsolidated sediments of the Cretaceous to Recent (< 70 Ma) Kalahari Sequence. This is shown in the table on "Aquifers and aquitards of the basin".

Hydrogeology

All groundwater within the basin flows towards the Etosha Pan, due to the structure of the basin and because as the pan, as the deepest point, is the base level of the groundwater flow system. Groundwater, recharged in the fractured dolomites of the Otavi Mountain Land, flows northwards

Aquifers and aquitards of the basin

Name of aquifers and aquitards, Hydrogeological character		Maximum thickness [m]	Lithology		Formation, Subgroup, Group	Groundwater quality and vulnerability
Unconfined Kalahari Aquifers (mainly porous, locally fractured)	DPA	Thin	Sand	n/a	Recent	Fresh, brackish during dry season, extremely vulnerable to pollution
	UKAEL	150	Calcrete, limestone; sand layers	Clay	Andoni (Etosha Limestone Member)	Fresh, locally high nitrate concentration, vulnerable to pollution
	UKAAN	50	Silt, clayey sand; calcrete layers	Clay	Andoni	Fresh to brackish
	MSAAN	70	Sand, calcrete	Siltstone		Brackish to saline, local fresh water lenses
Confined Kalahari Aquifers (porous to fractured)	OAAAN	100	Sand, gravel, sandstone	Clay		Fresh, Group B
	MDAAN	60	Sand, sandstone	Silcrete, lime-cemented sand, clay		Fresh to brackish (E of Okankolo), Brackish to saline (W of Okankolo)
	VDAOL	180	Sand, calcareous	Silcrete, lime-cemented sand, clay	Olukonda	Fresh (Angolan border, Eenyama, Okankolo) to saline (5 km south of Oshivelo)
	n/a	50	Sandstone, conglomerate	Mudstone	Beiseb	n/a
	n/a	100	Sandstone	Mudstone, shale	Ombalantu	n/a
Karoo Sequence Aquitard KSA (fractured, partly confined)		200	n/a	Basalt, sandstone, shale	Undifferentiated	Brackish, Group C, South of Oshivelo; Halali
		100	n/a	Basalt, dykes	Kalkrand	n/a
		140	Sandstone	n/a	Etjo	n/a
		220	n/a	Shale	Prince Albert	n/a
		160	Tillite	Shale	Dwyka	n/a
Mulden Group Aquitard, MGA (fractured, partly confined)		4200	Sandstone, quartzite, limestone, dolomite	Siltstone, shale	Owambo, Kombat, Tschudi	Saline (depth: 430 to 670 m) to slightly brackish (at shallow depth, Okaukuejo)
Otavi Dolomite Aquifer, ODA (fractured, partly karstic, partly confined)		4000	Dolomite, limestone	Shale, clay, schist	Tsumeb Subgroup	Fresh
		2000			Abenab Subgroup	Fresh (Otjuvasandu)
Nosib Group Aquitard		1200	n/a	Mixtite, sandstone, quartzite, conglomerate	Varianto, Nabis	n/a
Basement Aquiclude, (aquitard at shallow depth)		n/a	n/a	Granite, gneiss, meta-sediments, meta-volcanics	Fransfontein Granitic Suite, Khoabendus Gr.	Poor quality at Otjuvasandu

and feeds the aquifer system of the Karoo and Kalahari. However, a major part of this northbound groundwater flow is shallow, and discharges south-east of Namutoni through numerous springs along the southern margin of the Etosha Pan and through the bottom of the pan from where it rapidly evaporates. East of the groundwater divide (17° 45' E), the groundwater flow is most likely towards the Okavango River (1 100 m asl). The detailed hydrogeology of the different sediment layers is discussed, starting with the uppermost layers, working down.

The Kalahari Sequence comprises the Ombalantu, Beisib, Olukonda and Andoni formations. It is entirely of continental, aeolian to fluvial origin. The aeolian material consists of fine-grained, well-sorted sand, while the material deposited in a fluvial environment ranges from gravel to clay and often represents braided stream conditions, resulting in very variable lithologies both vertically and horizontally. Fluvial sedimentation dominates with some reworking of aeolian sand. Lacustrine clays and associated fluvial silts and sands were most probably transported by endorheric rivers flowing south from the north-west, similarly to the way that the Okavango River now feeds into the Okavango Swamps. The present pan floor consists of evaporitic calcareous sandstones covered by a thin layer of salt-bearing chalk.

At the southern and western margins of the basin, a rim of the Etosha Limestone Member is present close to the surface. It consists mainly of karstified calcrete, sand and minor clay and is interpreted as sedimentary-evaporitic limestone (groundwater calcrete). Stratigraphically, this unit is part of the Andoni Formation, but the carbonate composition of the rock indicates a separate facies and sedimentation milieu. The thickness of the calcrete increases from 20 m near Tsumeb to more than 150 m near Oshivelo and is therefore assumed to be a groundwater calcrete.

The Kalahari Sequence Aquifers are split into an unconfined and a confined to artesian part. The Unconfined Kalahari Aquifers (UKA) comprise two types of facies: the aquifer in the calcrete facies is classified as fractured, while the sand facies acts as a porous aquifer. The facies transition zone is located some 7 km south of Oshivelo (green/blue colour boundary on the Map). The Unconfined Kalahari Aquifer is subdivided into the Discontinuous Perched Aquifer (DPA) above the Main Shallow Aquifer ($\mathrm{MSA_{AN}}$) in the north, the calcrete facies ($\mathrm{UKA_{EL}}$) in the south and west, and the sandy facies ($\mathrm{UKA_{AN}}$) in the centre around Oshivelo. The Confined Kalahari Aquifers are the Oshivelo Artesian Aquifer ($\mathrm{OAA_{AN}}$) in the centre around Oshivelo and the Main Deep Aquifer ($\mathrm{MDA_{AN}}$) above the Very Deep Aquifer ($\mathrm{VDA_{OL}}$) in the north. The table shows these and provides an easy reference to the abbreviations used here.

$\mathrm{MSA_{AN}}$, $\mathrm{UKA_{EL}}$ and $\mathrm{UKA_{AN}}$ are stratigraphically equivalent; $\mathrm{UKA_{EL}}$ groundwater flows down-gradient into the $\mathrm{UKA_{AN}}$, while $\mathrm{UKA_{AN}}$ and $\mathrm{MSA_{AN}}$ groundwaters are mixed in the area of Omuramba Omuthiya and eventually discharge into the Etosha Pan (see arrows on the Map). $\mathrm{MDA_{AN}}$ and $\mathrm{VDA_{OL}}$ are likely to merge into $\mathrm{OAA_{AN}}$, however, the stratigraphic equivalence and hydraulic interconnection between the three aquifers have not yet been confirmed.

Schematic representation of the position of aquifers in the Cuvelai Basin

	North	Centre	South
Unconfined	DPA - Discontinuous Perched Aquifer		
	$\mathrm{MSA_{AN}}$ - Main Shallow Aquifer	$\mathrm{UKA_{AN}}$ - Unconfined Kalahari Aquifer	$\mathrm{UKA_{EL}}$ - Unconfined Kalahari Aquifer
Confined	$\mathrm{MDA_{AN}}$ - Main Deep Aquifer	$\mathrm{OAA_{AN}}$ - Oshivelo Artesian Aquifer	
	$\mathrm{VDA_{OL}}$ - Very Deep Aquifer		

The Discontinuous Perched Aquifer (DPA) is not a single aquifer, but consists of a series of small perched aquifers, which occur predominantly in the dune-sand covered area north-east of Okankolo. These aquifers are mainly recharged by direct infiltration of rainwater and exploited by means of "omifima", traditional, funnel-shaped dug wells. Although the yield is generally limited by the size of the aquifers, they provide shallow, easily accessible and good quality drinking water to the scattered villages of the Ohangwena and northern Oshikoto regions. The water quality is subject to seasonal variations, and may become brackish towards the end of the dry season. Because of the shallow water table, the Discontinuous Perched Aquifer is extremely vulnerable to pollution. Care must be taken to avoid contamination by dung at cattle drinking points.

Arnold Bittner

“Omifima” tapping the Discontinuous Perched Aquifer (DPA) in the Ohangwena Region

The Main Shallow Aquifer (MSA$_{\text{AN}}$) in the Andoni Formation is a shallow (6 - 80 m), unconfined multi-aquifer system which comprises a relatively thick sequence of layered sediments with competent, fractured sandstone aquifers, separated by less permeable aquitards consisting of clay and siltstone. The aquifer is tapped by a series of dug wells and has historically provided a large proportion of the water used in the central part of the Cuvelai Basin. The MSA$_{\text{AN}}$ occurs north of the Etosha Pan and Omuramba Omuthiya forms the south-eastern border. Groundwater flow is towards the Etosha Pan. The flat water table gradient is 0.2 ‰. The MSA$_{\text{AN}}$ is recharged once a year by floodwaters from Angola, that flow via the oshanas into Lake Oponono and can even reach the Etosha Pan in years of high flow. These large flood events are called “efundjas”. The water quality of the MSA$_{\text{AN}}$ varies from brackish to saline with local freshwater lenses on top of the saline water. The lenses form after flood events, mainly underneath the “oshana” channels and the water quality deteriorates during the dry season.

Within the thick karstified calcretes of the Etosha Limestone Member (UKA$_{\text{EL}}$), the depth to groundwater ranges from a few metres to 25 m below ground level (bgl). The transmissivity values range from 60 to 1 000 m^2/d. Yields vary from 1 m^3/h to more than 100 m^3/h in the Halali area and along the Tsintsabis - Oshivelo road, where the potential of the aquifer struck at depths between 70 to 90 m below ground increases westwards. The hydraulic continuity between the underlying Otavi Dolomite Aquifer dolomites and the Kalahari carbonates has not yet been proven. The age and salinity of groundwater increase along the flow path, particularly towards the Etosha Pan.

The Unconfined Kalahari Aquifer (UKA$_{\text{AN}}$) covers most of the area around Oshivelo and extends northwards towards the Omuramba Akazulu and then north-east towards the Okavango River. At Oshivelo, the UKA$_{\text{AN}}$ consists of 40 m silty to clayey sand-bearing fresh to brackish groundwater. The transmissivity is around 150 m^2/d, while yields are less than 10 m^3/h. Groundwater salinity deteriorates within a transition zone of only 5 km from Group B to Group D in a northernly direction.

The Oshivelo Artesian Aquifer (OAA$_{\text{AN}}$) was first penetrated at Oshivelo where it is separated by a 13 m clay layer from the overlying UKA$_{\text{AN}}$. It continues in a north-westerly direction and was intersected at depth in the Okashana and King Kauluma areas. Although not certain, it is assumed that the OAA$_{\text{AN}}$ extends as far as Tsintsabis in the east and the Omuramba Akazulu in the north, underlying the UKA$_{\text{AN}}$ in the Mangetti Duneveld. The southern aquifer boundary is defined by the transition between the calcrete and sand facies of the Unconfined Kalahari Aquifer, south of Oshivelo. The aquifer consists of sandstone, gravel and sand, partly lime-cemented and calcretised, separated from the upper aquifers by an aquitard comprising brown-green clay, calcrete and clayey sand.

In general, the deeper aquifers, underlying the southern

Dieter Plöthner

Hand-dug well within the Main Shallow Kalahari Aquifer (Oshikoto Region). The groundwater is saline and only suitable for livestock watering.

Arnold Bittner

Under pressure! Borehole penetrating the Oshivelo Artesian Aquifer with a free flowing yield of more than 200 m^3/h.

and eastern parts of the Etosha Pan and the area around Oshivelo up to Andonivlakte, are under artesian pressure. The boundary of this area, some 8 000 km^2 in size, is delineated on the Map. The piezometric head of the OAA$_{\text{AN}}$ groundwater is at 1 102 m asl. Where the surface elevation is lower, there is artesian flow. For instance, in 1923 in the Andonivlakte (1 080 m asl) the piezometric head of the OAA$_{\text{AN}}$ groundwater was 3 bars (304 kPa) or almost 30 m above ground level. An upper freshwater layer and a lower very brackish water horizon (TDS = 6700 mg/L) was struck and screened at an average depth of 170 m bgl. In 1971, the radiocarbon dating showed this groundwater to be 14 000 years old.

The values of transmissivity range from 3 000 to 10 000 m^2/d. The hydraulic conductivity is $8 \cdot 10^{-5}$ for the upper sandy, and $7 \cdot 10^{-3}$ m/s for the lower gravelly parts of the aquifer. The yield can be very high in the Oshivelo area (> 200 m^3/h) but decreases towards the north-west where the aquifer is less permeable. The OAA$_{\text{AN}}$ is recharged by throughflow from the Unconfined Kalahari Aquifer and the Otavi Dolomite Aquifer south of the Omuramba Owambo. In the Omuramba Omuthiya area, the groundwaters of the UKA$_{\text{AN}}$ and OAA$_{\text{AN}}$ become mixed and eventually discharge into the Etosha Pan. The salinity of the artesian groundwater ranges from 600 to 1 500 mg/L, deteriorating towards the north-west where concentration of total dissolved solids, TDS, exceed 2 600 mg/L (Group D).

The high groundwater potential in the surroundings of Oshivelo is indicated by the dark blue (OAA$_{\text{AN}}$) and the dark green (UKA$_{\text{EL}}$) colours on the Map. The sustainable yield of the aquifer was roughly estimated to be 2.5 Mm^3/a. A mathematical groundwater model suggests that, between Tsintsabis and Oshivelo, a groundwater flow of some 31 Mm^3/a is directed northwards from the dolomite areas around Tsumeb.

Generalised aquifer specifications of boreholes penetrating the OAA$_{\text{AN}}$ at Oshivelo

Depth [m bgl]	Aquifer thickness [m]	Lithology	Aquifer / Aquitard	Water quality
0 – 40	40	sand; white-green, calcareous, clayey	UKA$_{\text{AN}}$, MSA$_{\text{AN}}$	fresh to brackish
40 – 53	13	clay; seprolite; brown-green, sandy	Aquitard	–
53 – 67	14	silcrete and quartz sand; light brown	upper section of OAA$_{\text{AN}}$	fresh
67 – 81	14	sand, sandstone, gravel; white, light green	lower section of OAA$_{\text{AN}}$	fresh

The Main Deep Aquifer (MDA$_{\text{AN}}$) is present in the eastern Ohangwena and northern Oshikoto regions. The groundwater flow is southward, towards the Etosha Pan, while the recharge area is probably located in southern Angola. The southern and eastern boundary is uncertain and it is assumed that the confined MDA$_{\text{AN}}$ underlies the unconfined MSA$_{\text{AN}}$ in the Eenhana-Okankolo area. At King Kauluma, values of transmissivity range from 20 - 60 m^2/d and yield from 3 - 10 m^3/h.

The MDA$_{\text{AN}}$ is a continuous porous aquifer, which was intersected between Eenhana and Okongo at depths between 60 and 160 m bgl, representing the main freshwater source in the Ohangwena Region. West of the line Eenhana-Okankolo, the MDA$_{\text{AN}}$ is brackish to saline and cannot be developed for drinking water purposes. Towards the south, the water quality deteriorates over a short distance and is of Group D quality in the King Kauluma area, due to salinity and high fluoride concentrations. Mixing with waters welling up along fault systems from deeper aquifers causes further deterioration.

The Very Deep Aquifer (VDA$_{\text{OL}}$) was intersected at the same locations as the MDA$_{\text{AN}}$, but at depths of between 130 and 380 m bgl. The VDA$_{\text{OL}}$ is situated within the Olukonda Formation, which underlies the Andoni Formation in most parts of the Owambo Basin. Like the MDA$_{\text{AN}}$, the water quality deteriorates from north to south. The recharge area must be located in Angola. The water quality is fresh, east of Eenhana, but becomes more and more saline towards the south-west. In the south-western area, however, it is generally better than the quality of the MDA$_{\text{AN}}$, resulting in the situation that groundwater from

Flooded grasslands near Lake Oponono

Wynand du Plessis

boreholes penetrating the VDA$_{OL}$ at depth is fresh, while water pumped from the overlying MDA$_{AN}$ is brackish. This occurs at Okankolo, Onayena and Eenyama, where the upper saline aquifers are sealed off and fresh groundwater is pumped from the VDA$_{OL}$ to supply drinking water. No details on aquifer parameters and water quality are available for the Beisib and Ombalantu formations.

In the central Cuvelai Basin, the Karoo rock succession is made up of glaciogenic rocks (largely tillite with interbedded shales) of the Dwyka Formation, shales and coals of the Prince Albert Formation, and aeolian sandstone of the Etjo Formation (only at Nanzi). These lie on deeply weathered rocks of the Owambo Formation. Aeromagnetic surveys indicate basaltic lavas equivalent to the Rundu Formation in the south-east of the basin beneath the Kalahari succession. Recent drilling proved that the Karoo rocks including basalt lavas and dykes underlie the Kalahari sediments in the south of Etosha.

The Karoo Sequence Aquitard (KSA) comprises rocks such as shale, mudstone, sandstone and basalt. In general it acts as an aquitard with transmissivity values ranging from 1 to 10 m^2/d. However, locally it constitutes an aquifer. Three boreholes encountered pelitic sediments, while two boreholes struck weathered basalt. At four sites located between Tsumeb and Oshivelo, the Karoo shales and intrusives were penetrated at depths of between 160 and 400 m bgl. The system is semi-confined to confined. The Karoo aquitard hydraulically separates the underlying Otavi Dolomites from the overlying Kalahari Sequence. At Halali, some 100 km west of these sites, Karoo dolerite acts as an aquifer, where the hydraulic parameters are: Transmissivity, $T = 50$ m^2/d and hydraulic conductivity, $K = 6 \cdot 10^{-5}$ m/s. The water quality is Group C due to sodium concentrations above 400 mg/L.

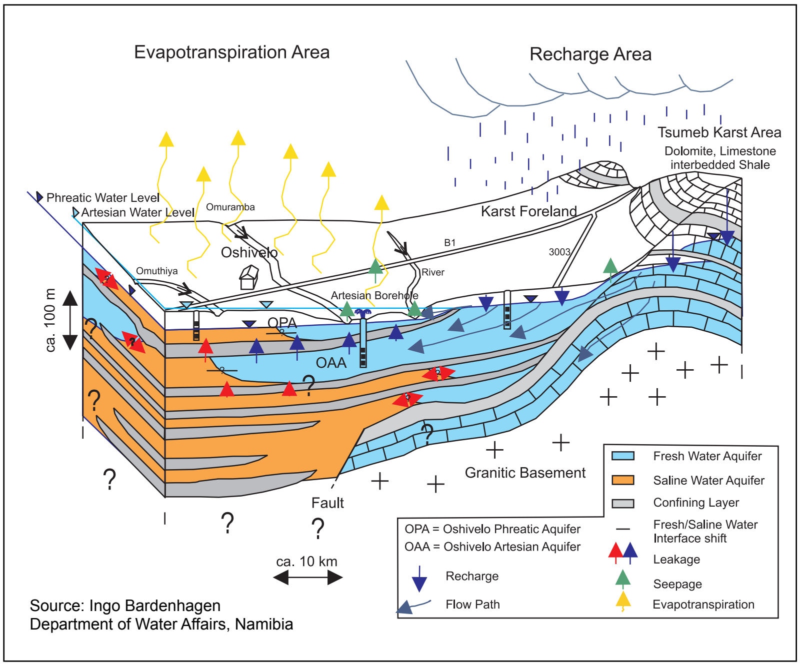
The lowest hydrogeological units in the basin are rocks of the Damara Sequence. Although these are described in detail in the section on the Otavi Mountain Land, they need to be mentioned briefly here, because of the hydraulic connections to the Cuvelai-Etosha Basin aquifers. The mostly fine-grained sediments of the Mulden Group Aquitard (MGA) are generally considered to act as an aquitard ($T = 3$ m^2/d), however, locally they can constitute an aquifer. At Okaukuejo, the Mulden Group constitutes a local fractured quartzite aquifer ($T = 300$ m^2/d, $K = 2 \cdot 10^{-4}$ m/s) and the groundwater is slightly brackish (TDS = 1400 mg/L).

The carbonates of the Otavi Dolomite Aquifer (ODA) constitute a thick fractured and partly karstified aquifer system representing the main hardrock aquifer in the southern part of the Cuvelai Basin. Artesian boreholes tapping the dolomite aquifer beneath Kalahari Sequence sediments are reported from the southern margin of the Etosha Pan. The dolomite groundwater is generally fresh (TDS < 1000 mg/L) in the Tsumeb area and to the north.

The rocks of the Nosib Group are considered aquitards based on experience in the area south of Tsumeb. The values of transmissivity range from 0.2 to 3 m^2/d, depending on the occurrence of faulted or non-faulted rock conditions. The basement generally acts as an aquiclude ($T < 5 \cdot 10^{-3}$ m^2/d), however, at shallow depth it may transmit small amounts of groundwater like an aquitard, for instance, in the Kamanjab inlier.

Groundwater quality and recharge

The quality of groundwater over much of the basin is extremely poor and severely limits its use. The water quality is especially poor in the central areas extending south from the Namibia-Angola border between Oshikango and Ruacana in a south-easterly direction towards Etosha and Oshivelo. On the Map, areas of saline groundwater are indicated by orange hatching, and the zone of saline water corresponds largely with the distribution of the Main Shallow Aquifer within the Andoni Formation (MSA$_{AN}$).



Source: Ingo Bardenhagen
Department of Water Affairs, Namibia

Block diagramme showing the recharge of the Oshivelo Artesian Aquifer

Except for brief periods of freshwater flows into the aquifer, this source is of very limited use. North-west of Oshivelo, dashed orange hatching on the Map hints at poor quality groundwater at depth, corresponding to deteriorating quality of the Oshivelo Artesian Aquifer groundwater southwards.

North of the Etosha Pan, the Kalahari and Karoo sequences and the upper part of the Owambo Formation form a large reservoir containing highly saline groundwater. The TDS ranges from 30 000 to 100 000 mg/L and chloride concentrations are 10 000 to 40 000 mg/L. The water quality improves as one moves eastwards, westwards and southwards from the central zone. The best quality groundwater is available along the basin rim in much of the Tsumeb area, in the entire north-eastern area of Ohangwena and Oshikoto, in south-western Omusati and Etosha, and in the Uukwaluudhi area north towards Ruacana.

Contrary to this general picture, relatively fresh groundwater can sometimes be found within the brackish central area, while places of saline water may be encountered in areas usually providing fresh groundwater (see small-scale inset map on "Groundwater quality"). Much of this patchiness is due to the fact that separate horizons in the same area can have very different qualities of water. Thus, a borehole may encounter a freshwater aquifer 50 m bgl, but deeper drilling can reach a brackish aquifer at 100 m depth.


Dieter Plöthner

Isotope sampling of a solar powered well in the Northern Central area

The mechanism of groundwater recharge in the Cuvelai Basin is not yet entirely understood. However, the following scenarios, supported by the results of a stable isotope study in the north and by numerical groundwater modelling in the south, are most likely to occur:

- Direct recharge from rainfall replenishes the Unconfined Kalahari Aquifers (UKA) in the north and in the centre at a rate of up to 1 mm or 0.2 % of the mean annual rainfall, and 0.25 % across the calcrete areas of the Etosha Limestone Member (UKAEL) in the south. In the north-eastern part of the basin, where annual average rainfall is above 500 mm, groundwater recharge occurs in the Kalahari sediments, as indicated by higher electromagnetic resistivities and relatively young groundwater ages.
- Indirect recharge through oshanas originating from Angola is likely to be the major driving force of groundwater recharge of the Main Deep Aquifer (MDAAN) and the Very Deep Aquifer (VDAOL) in the north. The age, determined by radiocarbon dating of the MDAAN groundwater increases from 2 000 years near Okongo to 15 000 years near Okankolo along its south-westerly flow path, while the VDAOL groundwater south-west of Okankolo is 35 000 years old.

Utilisation of groundwater

Since surface water is only available for certain periods in the Cuvelai Basin, people rely on other sources of water during dry periods. Access to groundwater was a key factor enabling people to settle in the basin many hundreds of years ago. Traditionally, the groundwater was tapped by dug wells. The western, southern and eastern areas of the region are supplied with groundwater from wells and boreholes. In 1991, 60 % of the water supply depended on dug wells, 10 % on drilled wells and 30 % on a pipeline system. During the 1990s, several drilling programmes were conducted, many for drought relief.


Kevin Roberts

Makalani palms typical of the Cuvelai Region

The central Cuvelai area with its predominantly saline groundwater (orange hatched area on the Map), is supplied by a complex system of canals and pipelines from Angola. Water stored in the Calueque Dam on the Kunene River just north of the border is pumped via a canal to the Olushandja Dam in Namibia, from where it is gravity fed via a concrete-lined canal to Oshakati. Olushandja Dam also supplies water by gravity via the unlined Etaka canal to Tsandi and Okahao, primarily for livestock watering. Drinking water is supplied to the same area by a pipeline parallel to the canal. The two canals and the major pipelines are marked on the Map.

In 2000, more than 100 000 people (about 15 % of the total population) still lived beyond the desired 2.5 km from safe drinking water. Government rural water supply projects aim to bring this number down by extending the surface water pipeline system and by drilling new boreholes. The main drilling target area is the Oshivelo Artesian Aquifer. Plans are to tap this aquifer using 3 production wells supplying some 2.5 Mm^3/a of fresh groundwater via a pipeline to the Oshivelo - Omutsegwonime - Okankolo area. There is a risk of salt water intrusion into the freshwater horizons, especially from the west and from underlying strata. Therefore the aquifer must be investigated in detail before its full potential can be used.

Eight water supply schemes based on groundwater and operated by NamWater abstract almost 0.9 Mm^3/a for drinking water, of which 0.5 Mm^3/a is supplied to three tourist camps in the Etosha National Park (see Box on opposite page).

For the communal farming area north of the Omuramba Owambo, the demand for livestock watering is approximately 13 Mm^3/a and is based on 1998 livestock estimates of 550 000 cattle and 1325 000 goats and sheep, and demand figures of 45 L/d per large stock unit, LSU, 8 L/d per small stock unit, SSU. About 0.6 Mm^3/a of groundwater is abstracted each year for livestock watering (31 000 LSU, 34 000 SSU) in the Tsumeb commercial farming area south of the Omuramba Owambo.

Groundwater-based irrigation is carried out on two farms: Mangetti Dunes and Namatanga (Kaokoland), vegetables are grown using drip irrigation. The water consumption rate is 10 000 m^3/a per hectare. Surface water is used for irrigation on three government farms near Ruacana and Oshikuku: Mahenne, Etunda and Ogongo. Two grow mainly vegetables on 10 - 12 ha of land each, while at Etunda 600 of the 1200 ha of irrigable land is used to grow vegetables, maize and wheat, using sprinklers. This watering technique uses twice the amount of water, 15 000 - 24 000 m^3/a per ha, that drip irrigation would for the same production.

A BITTNER, D PLÖTHNER

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Water supply of the Etosha National Park

The Etosha National Park, Namibia's best known tourist attraction, is one of the largest nature reserves in Africa, comprising an area of 22 270 km^2. The unique hydrogeological setting with 50 to 60 permanent springs, mostly contact springs situated along the southern rim of the Etosha Pan, has attracted man and wildlife throughout history.

Today, boreholes tapping groundwater from various aquifers supply most of the waterholes frequented by game, as well as the tourist camps. Many contact springs have dried up because the water table was lowered by pumping. Most of the waterholes are supplied by groundwater from the calcretes of the Unconfined Kalahari Aquifer (UKAEL). The calcretes cover the entire area south and west of the Etosha Pan. The calcrete groundwater quality is of Group A and B, i.e. suitable for drinking, only in the western and southern park area, declining to Group D, suitable only for wildlife and road construction, towards the southern rim of the Etosha Pan. Alternative groundwater resources had to be developed at greater depths for the three rest camps.

Wynand du Plessis

The Etosha National Park – unique hydrogeological setting with 50 to 60 permanent springs

At Okaukuejo, groundwater of Group B quality from a quartzitic horizon of the Mulden Group (MGA) is tapped to supply drinking water, while the Group C water of the calcretes is used for landscape gardening, the waterhole and the swimming pool.

At Halali, poor quality groundwater from the calcretes is pumped from the Klein Halali wellfield to the reservoir, where it is mixed with fresh groundwater of the Otavi Dolomite Aquifer (ODA) from the Renosterkom wellfield. This scheme is situated on a dolomite outcrop about 6 km south of Halali.

Drinking water for Namutoni is supplied by a wellfield at the Lindeque Gate 14 km east of Namutoni and taps groundwater from the Oshivelo Artesian Aquifer (OAAAN). The well at Namutoni on the same aquifer is slightly brackish and can only be used to fill the artificial game-viewing waterhole and for the camp gardens. The combined water consumption of the 3 tourist rest camps was 0.5 Mm^3/a in 1994 and is met by the aquifers, but water conservation is necessary to cope with the growing demand in the future. A total of 41 000 day visitors and 193 000 overnight guests were recorded in 1998, giving a relatively high average water demand of 210 L/d per tourist.

Wilhelm Struckmeier

Karstified dolomites close to the artificial water hole at Halali

A few waterholes for game watering in the west near Otjovasandu and south of the park at Ombika/Anderson Gate tap fresh groundwater (Group A) from calcretes, dolomites and quartzites. In contrast, the majority of the waterholes located in the central and eastern parts of the park provide brackish groundwater of Group C-D quality. Most of these do not meet the guideline values for human consumption and in cases exceed even those for livestock watering. The problematic parameters are TDS, sodium, chloride and sulphate. Poor quality water may also adversely affect wildlife.

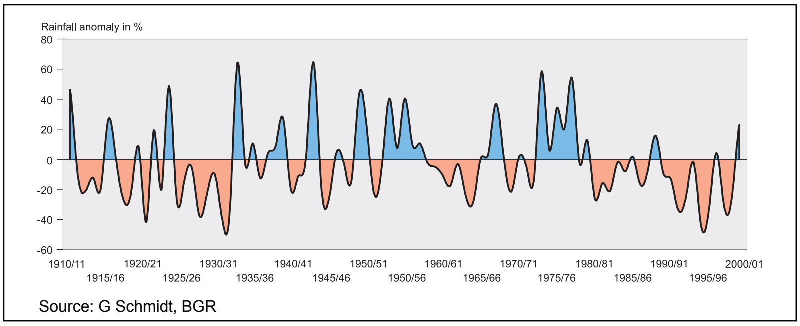
K DIERKES

Otavi Mountain Land

The hydrogeological region of the Otavi Mountain Land comprises the northern Otjozondjupa, the southern Oshikoto and the south-eastern Kunene regions. It stretches from the Otavi, Grootfontein, Tsumeb triangle in the east along the southern rim of the Etosha basin and westwards to 70 km beyond Outjo.

The Otavi Mountain Land is a dolomitic massif rising up to 2 090 m asl, some 500 m above the surrounding plains as shown in this photograph west of Hoba. In the south there is a gentle slope towards Goblenz (1 250 m asl) and northwards to Oshivelo and Etosha Pan (1 080 m asl). The Otavi Mountain Land represents a watershed draining westwards into the Ugab River catchment, northwards into the Etosha Pan, south and eastwards into the Omatako Omuramba, a tributary of the Okavango River.

The area receives a mean annual rainfall of 540 mm, decreasing to 450 mm towards Outjo. The graph shows the deviation of annual rainfall sums, based on the average from 50 stations, from the long-term annual mean (1926 - 1992) from 1911 to 1999. The large variation in rainfall with time is evident and amounts to 50 - 60 % of the mean. It is clear that the Otavi Mountain Land mainly received below mean annual rainfall over the past two decades. The mean annual potential evaporation is between 2 800 and 3 000 mm. Due to a mean annual rainfall double that of the country as a whole (540 mm/a vs 270 mm/a) and good quality soils, this commercial farming area is important for cattle and maize production. Most of the region has been declared a "Groundwater Control Area", underlining the national importance of its groundwater potential.



Source: G Schmidt, BGR

Deviation of the annual rainfall sums (average of 50 stations) from the long-term annual mean (1926-1992) for the time period from 1911 to 1999.

The area is also known for its high base metal potential, mainly copper, lead, zinc, silver and vanadium. The mines at Tsumeb, Khusib Springs and Kombat are operational, whilst those at Berg Aukas, Abenab and Abenab West have closed. The opposite table shows the characteristics of these mines and their potential to contribute to water supply. The ore bodies at depths of up to 1 800 m bgl are found along hydraulically favourable structures such as paleokarst cavities and fault conduits, and the mine water drainage rates can reach up to 12 Mm³/a. Some of this is purified and used for domestic water supply.

View, looking west, from Hoba over the dolomitic massif of the Otavi Mountain Land (Brandwag) rising above the surrounding plain where maize is grown

Dieter Plöthner

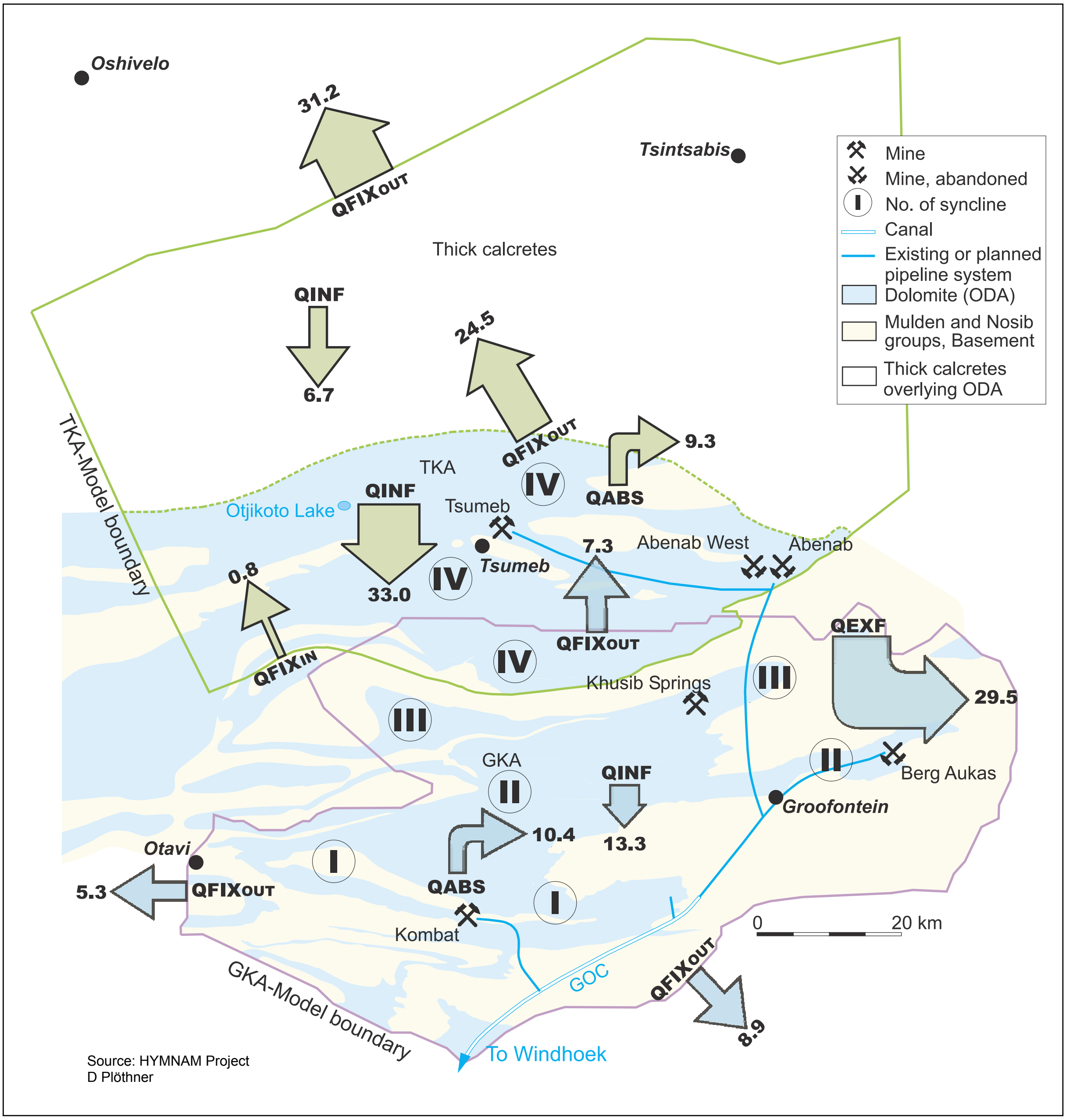
Geology

The Otavi Mountain Land lies on the northern shelf platform of the Otjiwarongo branch of the Damara Orogen. Approximately 6 000 m of sediments of the northern facies of the Damara Sequence have been accumulated on the granites and gneisses of the Grootfontein Basement Complex. The Proterozoic Damara Sequence consists of a basal arenaceous unit (Nosib Group, up to 1 500 m), a middle carbonate unit (Otavi Group, up to 3 000 m) and an upper clastic unit (Mulden Group, up to 1 700 m). The rocks of the Otavi Group have been stratigraphically subdivided into the Abenab and the Tsumeb subgroups and a number of Formations as shown in the table on stratigraphic succession. The dolomitic rocks contain interbedded layers of limestone, marl and shale. The strata were moderately folded during the Pan-African Orogeny (680 - 450 Ma) into several synclines and anticlines generally trending east-west evident in this map. From south to north, the three dolomite synclines are the Otavi Valley-Uitkomst (I), Grootfontein-Berg Aukas (II), Harasib-Olifantsfontein (III), and Tsumeb-Abenab (IV) synclinorium further north. The core of the synclines is filled with the low permeable rocks of the Mulden Group, whereas the anticlines reveal low permeable rocks of the Nosib Group and Basement.

The Kalahari Sequence is represented locally by a thin aeolian sand blanket and by calcretes which contain substantial amounts of silt and clayey material. The calcretes, in general, cover the low-lying groundwater discharge areas. They can be up to 20 m thick around Tsumeb, across the Nosib Anticline and the Basement high near Grootfontein, and up to 50 m thick near Brandwag/Uitkomst on the eastern tip of the Otavi Valley-Uitkomst Syncline (I). They widely cover the foreland where the thickness increases to 70 m towards the south and even 150 m towards the north.

Stratigraphic succession of the Otavi Mountain Land and its hydrogeological significance

System	Sequence	Group	Subgroup	Formation	Lithology	Average thickness [m]	Hydrogeological significance	
Quaternary, **Tertiary**	Kalahari (< 65 Ma)			**Karst Phase IV (34 000 to 14 000 a BP)**				
				Recent, Andoni	Aeolian sand, calcrete	20	Not considered	
				Disconformity (130-65 Ma), Karst Phase III				
Cretaceous, Jurassic, Triassic,	Karoo (300-130 Ma)			Rundu (Kalkrand)	Dolerite dykes in TKA	n/a	**Vertical Conduit**	
				Etjo	Aeolian sandstone	not pres.	n/a	
Permian, Carboniferous, Devonian, Silurian, Ordovician, Cambrian				Omingonde	Conglomerate, grit, mudstone	not present	n/a	
	Disconformity (550-300 Ma), Karst Phase II							
Namibian	Damara	Mulden (570-550 Ma)		Owambo	Marl, sandst., siltst., shale, limest., dolomite	not present	**Aquitard MGA**	
				Kombat	Phylitte, dolomite, conglomerate, shale	> 500		
				Tschudi	Arkose, grit, conglomerate, argillite	> 700		
		Disconformity (760-570 Ma), Karstic Phase I						
		Otavi (830-760 Ma)	Tsumeb	Hüttenberg	Dolomite, shale, chert	840	**Aquifer**	O D A
				Elandshoek	Dolomite	> 1200		
				Maieberg	Dolomite	180		
					Limestone, shale beds	700	**Aquitard**	
				Chuos	Quartzite, tillite, shale	200		
			Disconformity					
			Abenab	Auros	Dolomite, limestone	200	**Aquifer**	O D A
					Marl, shale	50	**Aquitard**	
				Gauss	Dolomite	750	**Aquifer**	
				Berg Aukas	Dolomite, limestone, shale	550		
		Disconformity (840-830 Ma)						
		Nosib (950-840 Ma)		Varianto (Ghaub)	Mixtite, quartzite	1200	**Aquitard**	
				Askevold	Phyllite, agglomerate			
				Nabis	Quartzite, arkose, conglom., schist, phyllite			
Mokolian		**Disconformity (1500-950 Ma)**						
		Grootfontein Basement Complex (Metamorphic Complex) (1580 Ma)			Granite, gneiss, shist, meta-gabbro (Grootfontein, Berg Aukas)	n/a	**Aquiclude / Aquitard at shallow depth**	



Source: HYMNAM Project
D Plöthner

Generalised geological map of the Otavi Mountain Land and the boundaries of the GKA and TKA numerical models

Doleritic dykes and dyke swarms with a length of several kilometres are present in the Tsumeb-Abenab Synclinorium (IV). These intrusive bodies of Karoo age intruded open axial tension structures and follow a roughly north north-west to north north-east direction. Water strikes are mainly related to these directions.

Four karstification periods of the dolomitic rocks of the Otavi Group have been found. The first and oldest period of karstification is presumed to have lasted from 750 Ma to 650 Ma in a period of uplift and erosion. A second karstification period interrupted by glaciation and sedimentation lasted from 450 Ma to 280 Ma. The third karstification period occurred in early Tertiary (65 Ma). The last major phase of karst processes developed during the Pleistocene approximately 34 000 to 14 000 years ago. These are shown in the table on stratigraphic succession. The fractured dolomites are karstified near the surface over a wide area and locally covered by soil. Deep karstification (e.g. Dragon's Breath Cave, Harasib Cave, Otjikoto and Guinas lakes) and paleo-karst (Tsumeb, Berg Aukas) only occur locally. The Hüttenberg Formation is the most highly karstified dolomite unit in the Tsumeb area, especially where it is covered by rocks of low permeability of the Tschudi Formation. Experience from Tsumeb Mine provides evidence of widely varying transmissivity values that range from 10 to 6 000 m^2/d.

Olifantsfontein Spring with discharge gauge

Dieter Plöthner

Hydrogeology

The high groundwater potential of the Otavi Mountain Land (dark green colour on the Map) is evident in the high inflow of groundwater into the abandoned Berg Aukas, Abenab and Abenab West mines and the operating Kombat, Tsumeb and Khusib Springs mines, the large perennial springs such as Otavifontein (1 Mm^3/a), Olifantsfontein (0.3 Mm^3/a) and Strydfontein (0.1 Mm^3/a), and former flows from the now dry springs at Grootfontein and Rietfontein.

The major springs (depicted on the Map) are contact springs bound to the contact dolomite/bedrock (Nosib or Basement) and have a fairly constant discharge, which according to isotope data originate from recharge at higher altitudes.

The depth to groundwater is relatively shallow (20 m bgl) south of Guinas Lake, whereas it may be more than 100 m deep below the higher altitude recharge areas north of Kombat Mine and south of Tsumeb as indicated by the contours on the Map.

In the Tsumeb area, Karoo dyke systems are considered as vertical conduits (T = 1 200 m^2/d) intersecting the entire multi-aquifer/aquitard system. The Tsumeb water supply wells are drilled into these structures.

The Kalahari calcretes do not form a major aquifer in the centre of the Otavi Mountain Land. Yields of 1 and 5 m^3/h have been reported for the area of the Nosib Anticline, however, with increasing distance from the dolomite outcrops it may become an important aquifer, especially northwards, where the calcretes of the Etosha Limestone Member are up to 150m thick south of Oshivelo. In the south, for example on the Farm Schwarzfelde, the calcretes have abundant ponors (karst holes) into which runoff, after heavy downpours, can percolate rapidly with little lost to evaporation. This type of indirect groundwater recharge is significant for the low-lying parts of the southern foreland.

The low permeable phyllites and quartzites of the Kombat Formation (Otavi Valley) and the Tschudi Formation (Tsumeb area) constitute the fractured Mulden Group Aquitard (MGA) with transmissivity values of 3 m^2/d.

From the top down, the Otavi Dolomite Aquifer (ODA) is composed of the fractured to karstified dolomite aquifer of Hüttenberg, Elandshoek and the upper part of the Maieberg Formations (Tsumeb Subgroup), while the thin-bedded limestone and shale of the lower Maieberg Formations act as an aquitard. For instance, north of Kombat Mine and in the Abenab area it separates the two abandoned mines hydraulically. The dolomites of the Elandshoek and Hüttenberg Formations have the highest average transmissivity values of 300 and 1 700 m^2/d respectively, and are therefore, the most important aquifers in the Tsumeb area, especially the Hüttenberg Formation.

The Chuos Formation ($T < 1$ m^2/d) crops out only in the south-west, where the weathered tillite and shale act as an aquitard separating the dolomite aquifer of the underlying Abenab Subgroup from the dolomite aquifer of the overlying Tsumeb Subgroup. The fractured dolomites of the Auros, Gauss and Berg Aukas Formations represent the

The numerical groundwater models of the Grootfontein Karst Aquifer (GKA) and Tsumeb Karst Aquifer (TKA)

Two three-dimensional numerical groundwater flow models have been established for the GKA and TKA, in which the GKA model includes the southernmost part of the TKA. The model areas and the calculation results are shown in the figure “Generalised map of the Otavi Mountain Land”. The opposite sketch outlines the flow system of the GKA. The calculated water balance figures are summarised in the table below. The GKA model simulation is for the period between 1979 and 1997 and is based on an initial calculated groundwater table distribution, which represents the hydraulic situation at the end of 1978, characterised by good replenishment during 3-4 years of above mean rainfall i.e. the system was relatively full. Within the TKA modelling, transient long-term calibration was executed for the period 1968-1998.

The values of horizontal hydraulic conductivities KH and storage coefficients S, assigned to the hydrogeological units, are shown in the table and in the schematic profile of the TDK.

	GKA model		TKA model (top layer 0-150 m)	
	KH [m/d]	S [-]	KH [m/d]	S [-]
Aquiclude	$3.5\cdot 10^{-3}$	$4\cdot 10^{-3}$	–	–
Aquitard	$3.5\cdot 10^{-2}$	$4\cdot 10^{-3}$	$1\cdot 10^{-2} - 7\cdot 10^{-2}$	$1\cdot 10^{-4} - 3\cdot 10^{-4}$
Aquifer	$3.5\cdot 10^{-1}$	$1\cdot 10^{-2}$	$1\cdot 10^{-0} - 7\cdot 10^{-0}$	$1\cdot 10^{-3} - 1.5\cdot 10^{-3}$
Aquifer (Grootfontein area)	$3.5\cdot 10^{0}$	$2\cdot 10^{-2}$	–	–

Small S values ranging from $1\cdot 10^{-4}$ to $1.5\cdot 10^{-3}$ indicate that confined groundwater conditions prevail in the TKA area.

The groundwater models have assigned potential recharge factors, e.g. in the TKA area 4 % (or 21 mm) for dolomite outcrops, 1.5 % (8 mm) for transition zone covered by less than 20 m thick calcretes, and 0.25 % (1 mm) for Mulden Group. Groundwater recharge rates based on results of an isotope study range from 0 to 9 mm (0-1.7 % of the mean annual rainfall). The calculated recharge factors for the GKA area vary between 1.3 % (7 mm) and 5 % (28 mm) of the mean annual rainfall. As an average over 19 years, the mean recharge factor for the dolomite outcrops of the GKA area is 1.7 % (9 mm), corresponding to a mean recharge rate of about 18 Mm^3/a.

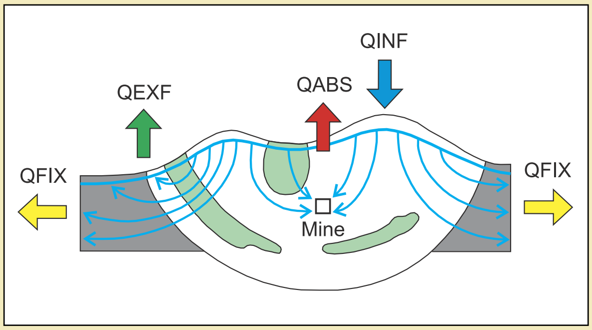
The discharge areas of the GKA model are springs or seeps where more vegetation occurs than in the surrounding area, e.g. at Khusib, Olifantsfontein, Mariabronn and at Brandwag. Due to the drought, the groundwater discharge of the springs and seepage (QEXF) dropped from 72.3 Mm^3/a in 1979 to 29.5 Mm^3/a in 1997.

The groundwater outflow across the system boundaries decreases with the decreasing hydraulic gradient. When the system was almost completely replenished in 1978, the total groundwater outflow ($QFIX_{OUT}$) from the modelled area amounted to 31.9 Mm^3/a (1978) decreasing to 21.5 Mm^3/a in 1997. The largest reduction occurred at the northern boundary with a decrease from 16.2 Mm^3/a in 1978 to 7.3 Mm^3/a in 1997, while in the south it decreased from 11.2 to 8.9 Mm^3/a and in the west from 6.8 to 5.3 Mm^3/a. Outflow to the east and west towards the Platveld Kalahari Basin is negligible.

Water balance of the groundwater models of the Grootfontein Karst Aquifer (GKA) and Tsumeb Karst Aquifer (TKA)

	GKA model			TKA model
Component of water balance	1979 [Mm^3]	1996/1997 [Mm^3]	1979 to 1997 Total amount [Mm^3]	2000 [Mm^3]
Groundwater reserves end-1978			**+3400**	
QINF	+12.8	+13.3	+370	+33.0
$QFIX_{IN}$	0.0	0.0	0	+0.8
$QFIX_{OUT}$	-31.9	-21.5	-450	-24.5
QEXF	-72.3	-29.5	-740	0.0
QABS	-5.7	-10.4	-170	-9.3
STOR	*-97.1*	*-48.1*	*-990*	*0*
Groundwater reserves end-1997			**+2410**	

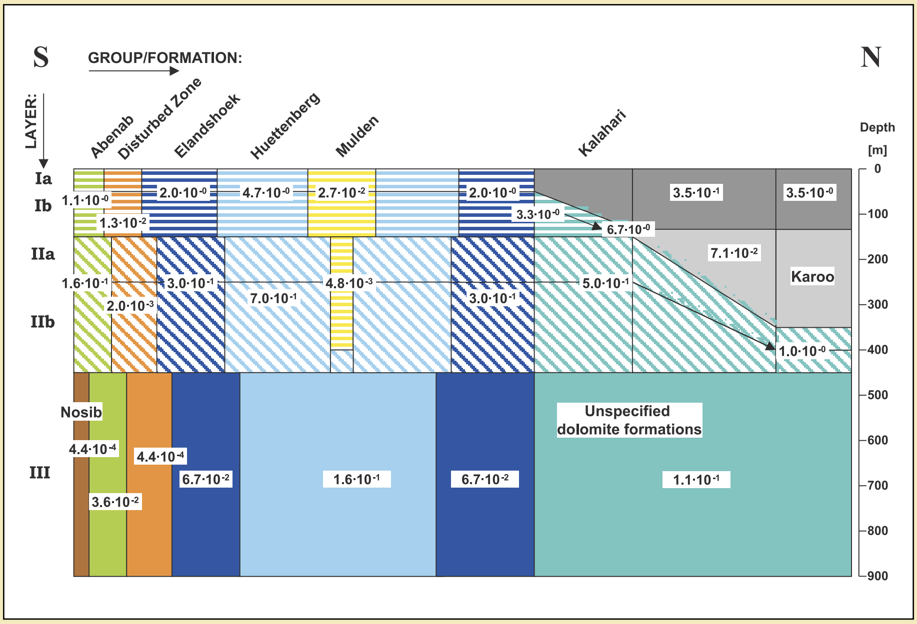
The 19-year (1979 to 1997) change in groundwater storage (STOR) totalled some 990 Mm^3 in addition to the cumulated recharge (QINF) of 370 Mm^3. Most (87 % or some 1190 Mm^3) were natural groundwater discharge



Fluxes of the GKA model

(QEXF + $QFIX_{OUT}$) and only about 13 % or some 170 Mm^3 (QABS) was abstracted, e.g. for Kombat Mine water drainage and domestic water supply to Grootfontein and Otavi. The potential groundwater reserves of some 3 400 Mm^3 stored in the upper 150 m of the saturated dolomites in 1979, were reduced by 29 % by the end of 1997 to 2 410 Mm^3. This resulted in a 10-30 m decline of the groundwater table in the highest central parts of the Otavi Mountain Land, representing the major recharge area of the system.

The GKA modelling results indicate that the determination of a sustainable yield and conventional development of the GKA dolomite aquifer system using relatively shallow wells may not be appropriate. However, the cavities formed underground represent easily accessible groundwater, which could in the short term be abstracted during prolonged periods of droughts at rates exceeding the sustainable yield. This can be conveyed via the Eastern National Water Carrier (ENWC) to the central areas of the country (Windhoek, Okahandja, Karibib, Otjihase and Navachab mines) to overcome temporary, emergency water shortages there.



Schematic north-south profile of the TKA. The data labels contain the depth related hydraulic conductivities [m/d] of the rock formations according to the 3-D model calibration.

As a result of the TKA model, the long-term sustainable groundwater abstraction rate has been assessed at about 4 Mm^3/a in addition to the present groundwater abstraction. Tsumeb and Abenab West mines are recommended abstraction points.

Applying an abstraction rate of 2 Mm^3/a at both mines and an annual increase of the current abstraction by 0.75 %, water levels at Abenab West Mine will decline by more than 100 m for average rainfall conditions from 2001 to 2016, and only by 10 to 20 m in the vicinity of the Tsumeb Mine. Further away, the water table will drop by 2 to 7 m and 25 to 40 m in the Tsumeb and Abenab areas, respectively. A net balance close to zero and no further significant decline in groundwater levels were predicted after a period of 60 years, indicating that steady state conditions will be reached after 2061.

For short-term (3 year) emergency bulk water abstraction, up to 10 Mm^3/a of groundwater could be abstracted from Tsumeb (7 Mm^3/a) and Abenab West (3 Mm^3/a) mines and exported to the central areas of Namibia, providing that the remaining water allocation does not exceed 5.5 Mm^3/a.

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major lower aquifer with transmissivities values ranging from 10 to 500 m^2/d. The 50 m thick shale of the lower Auros Formation acts as an aquitard, for instance, in the Abenab area.

The meta-sediments of the Nosib Group are considered a fractured aquitard (T < 1 to 3 m^2/d). The rocks with low permeability of the Nosib Group outcrop within the Nosib Anticline which separates the Grootfontein Karst Aquifer system (GKA) from the Tsumeb Karst Aquifer system (TKA). This results in relatively low groundwater flow from the south towards the north and is indicated by a very steep gradient of groundwater contours.

Mineralogical and hydrogeological characteristics of operating and abandoned Cu-Pb-Zn-Ag-V ore mines in the Otavi Mountain Land and their mine water quality, mine water drainage rates, and sustainable yields for water supply (ENWC)

<table>
<tr><th></th><th colspan="2">Khusib Springs Mine</th><th colspan="2">Kombat Mine</th><th colspan="2">Tsumeb Mine</th><th>Berg Aukas Mine</th><th>Abenab Mine (AM) / Abenab West Mine (AWM)</th></tr>
<tr><td>Type of deposit</td><td colspan="2">Cu-Pb-Zn-Ag</td><td colspan="2">Cu-Pb-Ag</td><td colspan="2">Pb-Cu-Zn-Ag</td><td>Zn-Pb-V</td><td>Pb-Zn-(V) deposit</td></tr>
<tr><td>Status</td><td colspan="2">operating since 1995, closed from 1997 to 2000, re-opened in April 2000</td><td colspan="2">operating since 1962, closed from Nov. 1988 to Sept. 1990 due to flooding, closed from 1997 to 2000, re-opened in April 2000</td><td colspan="2">operating since 1907, closed in August 1996 and flooded, re-opened in April 2000, since then operating up to 8th level; No.1 shaft, De Wet Shaft</td><td>operated from 1958 to 1978, No. 2 Shaft: sunk in 1968, gear head removed in 1996, four 360 m^3/h-pumps installed and linked with ENWC in 1997</td><td>AM operated from 1921 to 1947
AWM operated from 1947 to Jan. 1958</td></tr>
<tr><td>Syncline</td><td colspan="2">Harasib - Olifantsfontein (III)</td><td colspan="2">Otavi Valley - Uitkomst (I)</td><td colspan="2">Tsumeb Synclinorium (IV)</td><td>Grootfontein - Berg Aukas (II)</td><td>Tsumeb Synclinorium (IV)</td></tr>
<tr><td>Concentration of ore metals (production or ore reserves)</td><td colspan="2">6.5 % Cu, 1.2 % Pb, 1.4 % Zn, 350 g/t Ag</td><td colspan="2">3.1 % Cu, 1.1 % Pb, 26 g/t Ag</td><td colspan="2">5.8 % Cu, 3.5 % Pb, 1.2 % Zn, 0.04 % Cd, 179 g/t Ag</td><td>4.0 % Pb, 16.8 % Zn, 0.5 % V</td><td>AWM: 16 % Pb, 37 % Zn, (V)</td></tr>
<tr><td>Ore minerals</td><td colspan="2">tennantite, chalcocite, galena, minor sphalerite</td><td colspan="2">bornite, chalcopyrite, galena, chalcocite</td><td colspan="2">galena, tennantite, sphalerite, chalcocite, bornite, enargite</td><td>descloizite, sphalerite, chalcocite</td><td>descloizite, galena, cerrusite, willemite, limonite</td></tr>
<tr><td>Host lithology</td><td colspan="2">T2/T3 Maieberg Fm., limestone/dolomite contact; ore located in platy limestones of the T2</td><td colspan="2">T8 Hüttenberg Fm. dolomite overlain by phyllites of Kombat Fm., paleo-karst structures; Kombat West Fault acts as a major groundwater conduit</td><td colspan="2">Upper Elandshoek and Hüttenberg Fm., steep complex pipe-like paleokarst structure, filled with feldspathic sandstone, Mississippi Valley Type</td><td>Gauss and Berg Aukas Fm. dolomite with abundant karst cavities</td><td>AM: Maieberg Fm. dolomite, pipe-like ore body,
AWM: Auros Fm. dolomite, limestone</td></tr>
<tr><td>Depth of mining</td><td colspan="2">> 120 m</td><td colspan="2">> 800 m</td><td colspan="2">1800 m</td><td>750 m (No 2 Shaft)</td><td>AWM: 380 m
AM: 215 m</td></tr>
<tr><td>Type of ore</td><td colspan="2">sulphidic</td><td colspan="2">sulphidic/oxidised (> 60 m)</td><td colspan="2">oxidised/sulphidic ore (0-1500 m), sulphidic (> 1500 m)</td><td>sulphidic/oxidised (0-800 m)</td><td>oxidised/sulphidic (AW), mainly oxidised (Abenab)</td></tr>
<tr><td>Mine water quality (1997) with parameters exceeding Max. Admissible Concentration (MAC)
[*TH: Total Hardness]</td><td colspan="2">Group B: TH* (sampled in Jan. 2001)</td><td colspan="2">Group D: Al, Pb</td><td colspan="2">No. 1 Shaft: Group D: TH*, Ca, SO$_4$, Cd, Mn
De Wet Shaft: Group B: TH*, Fe, Pb, Mn; (purified for domestic water supply until 1996)</td><td>Group B: TH*</td><td>AWM:
Group B: TH*, Mg
AM: Group D: Fe</td></tr>
<tr><td>Transmissivity</td><td colspan="2">n/n</td><td colspan="2">n/a</td><td colspan="2">n/a</td><td>100 to 200 m^2/d</td><td>210 to 220 m^2/d</td></tr>
<tr><td>Storage coefficient</td><td colspan="2">n/a</td><td colspan="2">n/a</td><td colspan="2">n/a</td><td>0.005 to 0.01</td><td>0.011 to 0.012</td></tr>
<tr><td>Sustainable yield</td><td colspan="2">not yet established</td><td colspan="2">not yet established</td><td colspan="2">2.0 Mm^3/a</td><td>2.0 Mm^3/a</td><td>AWM: 2 Mm^3/a</td></tr>
<tr><td>Three year emergency yield</td><td colspan="2">not yet established</td><td colspan="2">not yet established</td><td colspan="2">7.0 Mm^3/a</td><td>4.5 Mm^3/a
6.5 Mm^3/a, if water-tight doors will be opened</td><td>AWM: 3 Mm^3/a
water-tight are presumed to be installed at all levels</td></tr>
<tr><td rowspan="6">Recent or former drainage rate (abstraction rate)</td><td>1995</td><td>0.3 Mm^3/a</td><td>1970</td><td>2.0 Mm^3/a</td><td>1907</td><td>0.7 Mm^3/a</td><td>AWM: up to 4.5 Mm^3/a</td><td>AWM: up to 5 Mm^3/a</td></tr>
<tr><td>2001</td><td>0.9 Mm^3/a</td><td>1988</td><td>6.0 Mm^3/a</td><td></td><td>6.0 to 9.5 Mm^3/a</td><td></td><td></td></tr>
<tr><td colspan="2" rowspan="4">80 % of mine water drainage is being artificially recharged into the aquifer</td><td>11/1988 - 09/1990</td><td>Flooded</td><td>1993</td><td>5.9 Mm^3/a</td><td></td><td></td></tr>
<tr><td>1992</td><td>4.7 Mm^3/a</td><td>June 1996</td><td>drainage ceased</td><td></td><td></td></tr>
<tr><td>1998</td><td>8.8 Mm^3/a</td><td>July 2000</td><td>drainage re-started</td><td></td><td></td></tr>
<tr><td>2001</td><td>12.3 Mm^3/a</td><td>2001</td><td>3.1 Mm^3/a</td><td></td><td></td></tr>
</table>

Dieter Plöthner

View over the head of No. 2 shaft of the abandoned Berg Aukas Mine: Four strong submersible pumps of which each has a capacity of 360 m^3/h were installed in the shaft in 1997 to lift groundwater from the open underground mine workings and the dolomitic host rock. The four pumps can be run simultaneously, but presently the set-up is two production pumps and one stand-by pump.

The granites and gneisses of the Basement are an aquiclude at great depth, however, at shallow depth, as in the Grootfontein area and in the Nosib Anticline, they act as a fractured aquitard ($T<0.005$ m^2/d).

Groundwater quality

The groundwater in the Nosib Anticline is predominantly characterised by the Mg/Ca-HCO_3 water type, the Total Dissolved Solids (TDS) range from 150 to 1200 mg/L. Locally, elevated sodium, chloride and nitrate concentrations occur in the vicinity of boreholes used for livestock watering.

The dolomite groundwater may be characterised as a low mineralised (TDS ~500 mg/L, from 150 to 1300 mg/L), very hard, near-neutral Ca/Mg-HCO_3 water. Within the irrigated areas of the Tsumeb Karst Aquifer, elevated sodium, chloride, sulphate and nitrate concentrations indicate contamination by irrigation return flows. Groundwater beneath irrigated land is subject to salinisation due to evaporation and the dissolution of fertilizer components. In this partly karstic terrain, the high vulnerability of groundwater to agricultural pollutants is of concern.

Some of the groundwater abstracted from the mines at Kombat is purified for drinking water purposes (until August 1996 this was also true for water from the Tsumeb mines). The water, regularly tested by NamWater, is suitable for drinking. The groundwater is sufficiently buffered to prevent heavy metals from the mines dissolving to any harmful extent despite the relatively high proportion of oxidised ore.

The table on the mineralogical and hydrogeological characteristics of the mines in the area show that according to tests in 1997, the water from Kombat, Tsumeb (No. 1 Shaft) and Abenab mines is of Group D quality and that of Tsumeb (De Wet Shaft) and Abenab West mines of Group B quality, as a result of the total hardness and unacceptable concentrations of aluminium, lead, calcium, cadmium, manganese, iron and magnesium. As experience from Tsumeb Municipality has shown, once treated, the mine water can be used for domestic supply as these metals are relatively easily removed by precipitation, and hardness is not a health concern. Because the groundwater in the mines is under pressure and supersaturated with calcite and dolomite, these and some of the heavy metals precipitate out at ground level and thus the water quality in the canal at the Okakarara off-take improves to Group A or B.

Utilisation of groundwater

This hydrogeological region hosts eight major water supply schemes of which Outjo (107), Kombat, Grootfontein (105) and Tsumeb (108) are independent waterworks, while the Otavi (79), Brandwag (16), Karstland (45) and Berg Aukas/Otjituuo (12) schemes and the stand-by abstraction scheme from Berg Aukas Mine are managed by NamWater. In 1999, these schemes abstracted over 7 Mm^3/a of groundwater.

Outjo waterworks produces 0.8 Mm^3/a of drinking water. Domestic water supply to the mine town at Kombat is 0.15 Mm^3/a and is abstracted through wells that belong to Ongopolo Mining and Processing Ltd., OMPL. The 20 wells at Grootfontein comprise four clusters of wells. In 1978, abstraction was 1.7 Mm^3/a, and this almost doubled to 3.2 Mm^3/a by 1997.

Until the early 1990s, the domestic water supply to Tsumeb Municipality was entirely dependent on the 2.5 Mm^3/a of groundwater supplied, and purified, from the mine. With time, as the ore body dwindled, the municipality drilled more than 15 production wells and until the Tsumeb Mine closed in June 1996, groundwater from the mine was purified and mixed with groundwater from the wells. Since then, groundwater abstraction by wells increased to a high of 3.1 Mm^3/a in 1997, but by 1999 had been reduced to 1.7 Mm^3/a. OMPL supplies an additional 1 Mm^3/a to the Tsumeb Municipality from 3 wells, north-east of the smelter.

Otavi is dependent on five wells and the inflow of an

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Otjikoto Lake, one of the Karst sinkholes in Namibia

eighth of the total spring discharge of Otavifontein. The total production of local waterworks amounts to 0.5 Mm^3/a.

The Brandwag wells form the first phase of the Karstland scheme. These relatively shallow wells are sited along the south-eastern tip of the Otavi Valley-Uitkomst Syncline (I) next to the Nosib bedrock contact. Due to the prolonged dry period and low recharge, the scheme is currently dry. The Karstland scheme comprises some stand-by wells east of Kombat Mine and one well gallery of 20 stand-by wells tapping the dolomite aquifer of the Harasib-Olifantsfontein Syncline (III). These are shown on the Map. Tests done in 1996 estimated a total yield of 3 Mm^3/a for this scheme, yet it has never been fully implemented nor linked to the Eastern National Water Carrier, ENWC.

Groundwater abstraction at the Berg Aukas-Otjituuo scheme started in 1986. Some 0.7 Mm^3/a from two strong wells is piped to Otjituuo to augment the local water supply . Until it closed in 1978, Berg Aukas Mine drained more than 4 Mm^3 of groundwater annually. In 1996, the gear head of No.2 shaft was removed and 4 strong pumps each with a capacity of 360 m^3/h were installed in the shaft shown in the photograph. In 1999, an 80-day test run at discharges varying from 5 to 8.5 Mm^3/a transferred 2 Mm^3 of groundwater from the mine into the ENWC. Results showed that the long-term sustainable yield is assessed to be 2 Mm^3/a at an expected drawdown of up to 150 m bgl, and that should it be necessary to cope with a 3-year water emergency in the central region, the yield could be increased up to 6.5 Mm^3/a with an expected drawdown of up to 400 m bgl.

Water abstraction from the Khusib Springs and Kombat mines continued between 1996 and 2000, and after the take-over of the mines by Ongopolo from Tsumeb Corporation Limited, TCL, ore production recommenced in April 2000. From 1995, when mining operations at Khusib Springs Mine commenced, water drainage increased from 0.3 Mm^3/a to 0.9 Mm^3/a in 2001. About 80 % of the drained mine water is being artificially recharged into the dolomite, while 20 % is used for ore dressing and to keep dust down. Kombat Mine increased the mine water drainage rate from some 2 Mm^3/a in 1970 to more than 6 Mm^3/a in November 1988, when the mine was accidentally flooded. Since October 1990, when mining operations resumed, mine water drainage increased from 5.5 Mm^3/a to 12.3 Mm^3/a (1 400 m^3/h on an average) in 2001. Nearly half, 5.7 Mm^3/a, of the mine water drained is exported via the ENWC, a quarter, 3.1 Mm^3/a, is used for ore dressing, processing and dust depression, 22 % or 2.6 Mm^3/a for irrigation of the golf course and public gardens in Kombat, and the remaining 0.9 Mm^3/a is supplied to two commercial farmers to grow maize. As there is 250 ha of irrigable land in the vicinity of Kombat Mine, up to 4 Mm^3/a of the mine water could be used for irrigation. Between 1998 and 2001 an average of 2.3 Mm^3/a of Kombat Mine water supplied the Okakarara treatment plant from where it can be piped further to Otjituuo, as depicted on the Map. In October 2001, OMPL and NamWater negotiated an assured supply of 4.4 Mm^3/a from the mine for export to the ENWC at a price of 0.35 N\$/m^3.

From 1921 to 1947, when still operational, Abenab Mine drained 3 to 4 Mm^3/a, this increased to 4.4 Mm^3/a in the last four years of operation (1955 - 1958) from Abenab West Mine. Groundwater is still abstracted for irrigation purposes at a rate of 0.2 Mm^3/a.

Annual drainage from the Tsumeb Mine was between 6 and 9.5 Mm^3. In 1993, 5.9 Mm^3/a of groundwater was abstracted from the De Wet Shaft, of which 2.9 Mm^3/a was used by TCL for the ore washing plant and smelter and about 2.5 Mm^3/a supplied to Tsumeb Municipality. In the early 1990s, the oval-shaped cone of depression of the mine extended some 9 km east-west and about 8 km north-south.

When mining and hence drainage ceased in June 1996, Tsumeb Mine got flooded, and due to the complicated karst hydrology of the mine workings, the water table rose slowly up to 60 m bgl. By the end of July 2000, after the take-over of the mine by OMPL, drainage recommenced. The water table dropped to 240 m bgl, where it is currently maintained. Groundwater was initially drained off at 5.3 Mm^3/a but decreased to 3.1 Mm^3/a in 2001. About 20 % of the mine drainage water is used on public gardens by the Municipality of Tsumeb and the rest for ore dressing and processing, the smelter, and keeping down dust at the mine.

In summary, Kombat and Berg Aukas mines can supply from 6.4 Mm^3/a to 16.5 Mm^3/a to the ENWC, the latter only in emergencies. As soon as Tsumeb and Abenab West mines are linked to the ENWC, the water supplied by mines could be increased by 4 to 10 Mm^3/a, totalling 10.4 to 26.5 Mm^3/a.

Some 90 irrigation farms rely on groundwater within the Otavi Mountain Land and its foreland, especially in the northern Tsumeb area where 83 farms abstract groundwater to grow vegetables, maize, wheat, lucerne, cotton, and citrus. Although only 1100 ha or 0.1 % of the Tsumeb Karst Aquifer area is under irrigation, 5.7 Mm^3/a or 55 % of the total groundwater is abstracted from the TKA for irrigation.

As shown in the water balance of the Grootfontein Karst Aquifer, more than 0.3 Mm^3/a is pumped from Otjikoto and Guinas lakes for irrigation. The two lakes are collapsed sinkholes (dolina) in the dolomites of the Maieberg Formation and are the only permanent lakes in Namibia. The lakes have a diameter of 100 and 140 m and a depth of more than 75 and 150 m, respectively, and provide "windows" to the groundwater. They are also home to one of Namibia's rare, endemic fish species, the Otjikoto tilapia. Isotope data suggest that recharge to the two lakes is from altitudes from 1600 to 1900 m asl, somewhere south of Tsumeb or north of Kombat. The travel time of the groundwater from the southern recharge areas to the lakes is estimated to be only 30 - 40 m/a. West of Guinas Lake there are two other collapsed sinkholes on the farms Hoasis and Obab. Even though these are dry, boreholes sunk into the filling of the sinkholes abstract groundwater for small-scale irrigation, livestock watering and domestic water supply.

In the GKA area, there are only 7 irrigation farms and some 255 ha of land under irrigation, of which 185 ha is irrigated by Kombat Mine groundwater, 20 ha by spring water from Otavifontein and the remaining 50 ha by groundwater abstracted via boreholes. Rietfontein Farm, one of the few dairies in the country, stopped irrigation when Rietfontein spring dried up in 1989. In 2001, this large farm used 0.25 Mm^3/a of groundwater abstracted by boreholes.

Groundwater use for livestock farming is the same in the Tsumeb Karst Aquifer area and Grootfontein Karst Aquifer area, each use approximately 1 Mm^3/a.

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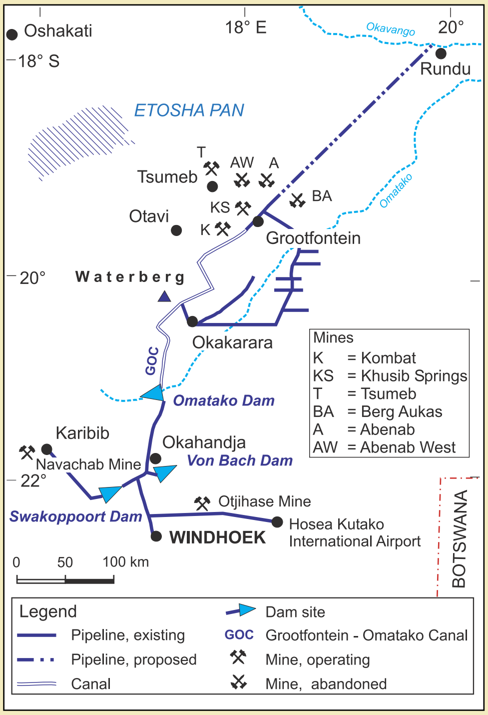
The Eastern National Water Carrier (ENWC) and the Grootfontein-Omatako Canal

The Grootfontein-Omatako Canal was built between 1981 and 1987. The Kombat Mine is connected to the canal via a 20 km long pipeline. The canal is 263 km long, of which 203 km is a parabolic, open and concrete-lined canal and the remainder consists of 23 inverted siphons or underground pipes. The canal has a maximum width of 3.7 m and a maximum depth of 1.65 m. It is a gravity flow canal with a gentle slope of about 1: 3 000. When full, the flow velocity is 0.8 m/s and the maximum capacity is 3 m^3/s (95 Mm^3/a).

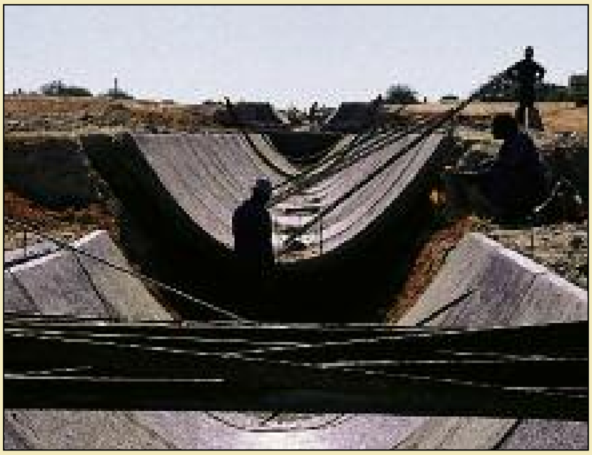
The canal passes through commercial farmland and for 60 km it runs parallel to the Waterberg. The canal with its steep parabolic sides has become a death trap for frogs, snakes, tortoises, warthogs and several rare protected species. Up to five thousand wild animals drown each year, proving that a steep sided open canal is not an appropriate water carrier in a semi-arid country with abundant wildlife.



Diagrammatic layout of the Eastern National Water Carrier (ENWC)

The Grootfontein-Omatako Canal, as part of the ENWC, conveys groundwater from mines in the Otavi Mountain Land to rural areas in the Okakarara District, and to the Omatako Dam from where it is further distributed by pipelines to the central areas of Namibia, including Windhoek, Okahandja, Karibib and Navachab and Otjihase mines. See the diagrammatic layout showing the infrastructure of the ENWC and route on the Map. At present, Kombat Mine, Berg Aukas Mine as a stand-by water supply scheme, and some stand-by wells are linked via pipelines to the canal. The feasibility of linking the Tsumeb Mine and the abandoned Abenab West Mine to the canal is under investigation. In good rainfall years, the three dams linked by the ENCW, Omatako Dam, Von Bach Dam and Swakoppoort Dam, can impound sufficient volumes of ephemeral river runoff to meet the water demand of central Namibia. Kombat Mine groundwater is treated at Okakarara to meet the demands of the town and for rural water supply in the district. The intention is to supply groundwater from Kombat and Berg Aukas mines to central Namibia during prolonged droughts, when surface water is scarce.

There is a proposal to link the canal via a 240 km long pipeline to the Okavango River, to supply the central areas of Namibia. However, the possible environmental impact of large scale water withdrawal from the river both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Grootfontein-Omatako Canal under construction

on the ecology of the river downstream and on the unique wetlands of the Okavango Swamps, has yet to be fully assessed. The Okavango River catchment is internationally shared by Angola, Namibia and Botswana, thus all major developments must be agreed to by the other basin states. The tripartite Okavango Commission, OKAKOM, was created in 1994 as a forum for such debate and an Okavango River Basin Management Project is planned with the financial assistance of the Global Environment Facility (GEF). A preliminary agreement has been signed curbing any significant developments in the catchment by any of the States until a management plan for the Okavango River basin has been jointly established.


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Inflow of groundwater from Brandwag into the ENWC

The current strategy of the Department of Water Affairs and NamWater is, prior to the Okavango option, to investigate the feasibility of groundwater abstraction from the abandoned mines of Berg Aukas and Abenab West and the operating mines at Kombat and Tsumeb. Both options, either on a long-term sustainable yield basis or on a short-term emergency basis (allowing higher abstraction rates for up to 3 years), are being investigated. Additional groundwater for the ENWC could in future, be abstracted from stand-by well galleries in synclines I and III.

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Inflow of the Grootfontein-Omatako-Canal into the Omatako Dam

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Northern Namib and Kaokoveld

The Northern Namib and Kaokoveld groundwater region is located in north-western Namibia. The boundaries, chosen on the basis of landforms and hydrogeological significance, coincide more or less with the Kunene Region. Its north-eastern dolomitic mountain ridges represent the eastern rim of the Cuvelai Basin. In the south it is bordered by the Ugab River and the Brandberg.

From the Ugab River northwards, the Namib is described as a rocky desert. The average rainfall ranges from less than 50 mm/a in the west to slightly more than 300 mm/a in the east. Except for the Kunene River, all rivers are ephemeral: these are the tributaries of the Kunene flowing north, e.g. Otjinjange, Omuhongo and Ondoto, and the westward-flowing ephemeral rivers (from north to south), Nadas, Sechomib, Khumib, Hoarisib, Hoanib, Uniab, Koigab, Huab and Ugab. Most of the land is state protected or communal area. Commercial farmlands are present in the Khorixas District.

Most of the Namib areas are hills and valleys while the Kaokoveld further north is rugged mountain terrain. The escarpment separates the Skeleton Coast coastal plain in the west from the mountainous areas in the east. Prominent landmarks are the Baynes and Hartmann's Mountains in the north, and the Etendeka table mountain landscape in the south-west. East of Khorixas are the Ugab terraces with the famous Fingerklip.


Shirley Bethune

Epupa Falls on the Kunene River

The northern part of the area is populated by the Himba and the southern part by Damara people. Both are stock farmers keeping cattle, goats and sheep. The administrative centres of the Kunene North and South regions are Opuwo and Khorixas respectively. Kamanjab, a town located 100 km north of Khorixas, serves the local commercial farming community.

Geology

Granitic and gneissic rock types cover vast areas in the Kaokoveld. Granites, gneiss and old volcanic rocks are roughly located in a triangle between Marienfluss, Swartbooisdrif and Sesfontein. Metamorphic rocks including marble and quartzitic bands occur in the western part of the Kaokoveld. They form a strip between the Hartmann's Mountains and the coast that goes all the way down to the Uniab River.

Mountain ranges of carbonate rock types (dolomites and limestones of the Otavi Group) that can be related to the Otavi Mountain Land, form the eastern edge of the area, grading towards the north into outcrops of quartzitic sandstone representing the Nosib Group. The Baynes Mountains in the far north are also dolomitic and quartzitic rocks of the Otavi and Nosib groups.

Volcanic rocks of the Etendeka Formation crop out between Sesfontein and the Huab River. Some smaller units are present in the area south of Orupembe. These volcanic rocks build the typical table mountain landscape of Damaraland. Underlying shale and mudstone of the Dwyka Formation are present in the area west and east of Orupembe, in the Opuwo area, west of Sesfontein and at Ruacana. The most recent rocks are calcretes (in the area of Khorixas, Fransfontein and Sesfontein) as well as alluvial deposits occurring locally in the ephemeral river beds.

As far as tectonic structures are concerned, the most well known ones are the Sesfontein Thrust and the Purros Lineament. The Sesfontein Thrust represents the contact between the Otavi Dolomites and metamorphosed rocks, represented by phyllites of the Mulden Group. This contact zone gave rise to the springs found at Sesfontein. The topographical location of the contact, on top of a hill, makes it impossible to intersect by boreholes. The Purros Lineament has been investigated hydrogeologically but is not productive, despite some good yielding boreholes drilled on the lineament.

Hydrogeological features and utilisation of groundwater

The region generally has a low groundwater potential. The area with aquifer potential, more or less reflects the rainfall distribution, decreasing westwards. Knowledge of the aquifers in this area is sparse, due to the low number of boreholes and few government investigations on groundwater.

Gwendal Madec

Spring east of Kaoko Otavi

The area is well known for its numerous springs that provide water for wildlife and to villages. Small-scale irrigation schemes are in operation at some of the higher yielding springs, like Warmquelle, Kaoko-Otavi and Sesfontein. There are also a number of thermal springs in the area, e.g. Warmquelle, Ongongo, Monte Carlo and springs at Okangwati. Other well-known springs are Fransfontein, Gainatseb, Palmwag, Sarusas and Orupembe. The Sarusas spring, located in the lower reaches of the Khumib River, provides drinking water to wildlife in the Skeleton Coast Park.

Recharge from rainfall is an important parameter determining the groundwater potential, but the degree of metamorphism effects the groundwater potential too. The groundwater potential of rocks decreases, as the degree of metamorphism increases. Crystalline rocks, such as the various granites and gneisses that occur in the area, normally exhibit a very low tendency to store water. Unfortunately, as indicated by the lithology, most of the Kaokoveld is underlain by rock that is either granitic, gneissic or metamorphosed. Therefore, the dark brown colours on the Map, representing aquifers of very low potential, prevail in a triangle between Swartbooisdrif, Kunene River mouth and the Uniab River mouth. Drilling targets in these hard rock areas are mainly fractured zones and faults, but the success rate and yields for these rock types are generally low. This can be considered as one of the most difficult areas to drill for water. The area surrounding Okangwati is more promising due to well-developed fractures and faults that give rise to hot water springs.

Another zone of crystalline rocks, classified as granites, gneisses and old volcanic rocks, underlie a more or less triangular area between Otjovasando, Outjo and the confluence of the Huab and Aba Huab rivers.

In geological terms this is known as the Kamanjab Inlier and the Khoabendus Formation. The groundwater potential of this rock unit is generally low, to locally moderate; it improves as one goes further east, in the direction of increasing precipitation. Pump-tests done on boreholes in the Kamanjab area, however, illustrate that recharge is still limited and does not occur very often in the western parts of this zone, an area of mostly commercial farmlands.

Kamanjab is a town that has outgrown its groundwater potential. The rocks of the area around Kamanjab (meta-sediments and granites of the Huab Complex overlain by volcanic rocks and meta-sediments of the Khoabendus Group) have very little groundwater potential. A wellfield (42) to supply the town is clustered around a small earth dam that fails to provide significant recharge. Additional boreholes drilled in the volcanic rocks at the airfield on the farm Kamanjab Nord have similar low yields and limited reserves. Recently, a new wellfield was installed on the farm Kalkrand East east of Kamanjab in calcrete-covered Huab Complex, and dolomites of the Otavi Group north-east of Kamanjab were also investigated as potential groundwater supply sources.

Other small water supply schemes in crystalline rocks are

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Skeleton Coast, Khumib River: Sarusas spring near Wilderness Rest Camp

for the schools at Anker and Erwee. Anker (6), a school in the northern Brandberg area is supplied with water from three boreholes drilled on fractures in quartzite and granite of the Huab Complex. The water quality has deteriorated from Group B to C due to over-abstraction. Erwee (26) was established on the farm Grootberg west of Kamanjab in an area underlain by granite and meta-sediments of the Huab Complex. The low storage capacity of the rocks combined with erratic recharge and high consumption soon led to over-abstraction of the aquifer.

The carbonate rocks (limestones and dolomites) of the Otavi Group, located in the north-east of the area have moderate potential and are indicated by a light green colour on the Map. Nevertheless, where in contact with other rock types, particularly the non-porous sandstone, conglomerate and quartzites of the Nosib and Mulden Groups, weathering is enhanced by karstification processes and higher yields can be expected. These contact areas are indicated by dark green lines on the Map.

The water supply scheme of Sesfontein (93) owes its origin and name to the six fountains along the contact zone between dolomites of the Tsumeb Subgroup dolomite aquifers and the underlying less permeable phyllites of the Mulden Group (both Damara Sequence). A fort was built in this favourable place in colonial times. As the town expanded, the water supply from the fountains was supplemented by boreholes, which in turn reduced the flow from the fountains. The yield of the water scheme is currently insufficient to meet the growing demand.

Another thin band of Otavi dolomites and limestones extends all the way from the Otavi Mountain Land to the Fransfontein area. The southern contact of this dolomite ridge is a good drilling target for establishing productive boreholes (indicated as dark green) but the northern contact is less productive. Fransfontein owes its origin to springs issuing from the dolomites. The springs are however not used for human consumption. Instead groundwater is supplied from boreholes on fractured dolomite for the Fransfontein water supply scheme (27).

The Khorixas water supply scheme (47) is similar. Groundwater is pumped 30 km away from Braunfels where high-yielding boreholes are drilled into calcretes underlain by fractured dolomite of the Otavi Group.

The Gainatseb spring yielding between 80-100 m^3/h also forms part of this scheme and contributes to the water supply of Khorixas, a sprawling town with an uncommonly high water demand. Other thick groundwater calcrete deposits in the Khorixas area, known as the Ugab terraces, are drained by the Ugab River itself and contain little groundwater.

Mudstones and shales of the Chuos Formation are found between the Otavi Group dolomites. The groundwater potential of this unit is very limited but the dolomite in contact with the Chuos is karstified at the contact plains and provides high-yielding boreholes. High concentrations of iron are associated with the groundwater in the Chuos Formation.

The groundwater potential of the shale and mudstone deposits belonging to the Dwyka is generally very limited. Where the Dwyka sediments have been deposited in deep incised glacial valleys, the potential is better as illustrated by the Opuwo wellfield and at Ruacana. Most of these better-yielding boreholes have been drilled on the sides of these deep valleys, but sometimes give water quality problems.

The water supply scheme of Opuwo (76) comes from a Dwyka shale aquifer, known as the north-western wellfield, and from a sandstone and shale aquifer of the south-eastern wellfield. Yields of the sandstone aquifer are low but that from the north-west wellfield exceed 15 m^3/h, but the water quality falls in Group C and D.

Little is yet known about the groundwater potential of the young volcanic rocks of the Etendeka Formation. As numerous springs issue from these rocks all over the area, the groundwater potential is expected to be higher than that of the metamorphic and granitic rocks. Most of the Etendeka is however located in the far west, where direct recharge from rainfall only occurs infrequently. The water supply scheme of the Bergsig (13) settlement and school obtains its water from fractured basalt of the Cretaceous Etendeka Formation. The stored reserves are limited and recharge is low. In contrast, where boreholes and wells have been sunk in the eastern, higher rainfall area, the yields are significantly higher. Some of the most exclusive wilderness resorts, such as Etendeka Mountain Camp, rely on these springs and are appropriately managed to keep the water consumption to the minimum.

In the ephemeral rivers, alluvial groundwater is in many cases tapped by boreholes and hand-dug wells. It provides an important groundwater resource, especially in the western half of the area. Boreholes drilled in bedrock nearby are also sustained by alluvial groundwater. The groundwater potential of these drainage lines is considered far better than the surrounding rock. This is indicated by light blue on the Map. To improve the sustainability of boreholes drilled in poor productivity areas, it is common practise to artificially recharge the groundwater bodies using small-scale dams (ground swells or sand dams) built in the riverbed.

The camp at Terrace Bay is supplied with water from the alluvial aquifer in the Uniab River, 20 km to the south. The river flows infrequently but when it floods it can destroy the production boreholes. The water quality varies from Group A-D depending on recharge, as the salinity increases with time, due to evaporation.

The entire area is dependent on groundwater resources for domestic purposes and stock watering. Since communal farmland occupies most of the area, the Directorate of Rural Water Supply is responsible for most of the water supplied to these farms. Water supply schemes operated by NamWater provide groundwater to the urban centres of Khorixas, Opuwo, and Kamanjab, as well as to some of the smaller villages such as Anker, Bergsig, Erwee and Fransfontein.

P BOTHA, A VAN WYK

The Brandberg, Erongo and Waterberg Area

The Brandberg, Erongo and Waterberg groundwater area includes the Waterberg in the north-east and stretches down to the Atlantic coast in the south-west. It covers most of the western part of the Otjozondjupa Region and the northern Erongo Region. Otjiwarongo and Okahandja are situated on the eastern edge of the area. The Waterberg Plateau Park run by Namibia Wildlife Resorts is a major tourist attraction dependent on groundwater within this area.

Most of the area is more than 1 300 m above mean sea level. Westwards, within an approximately 100 km-wide zone, the land surface drops to sea level. The eastern portion of the area is of relatively flat topography with dispersed inselbergs like the twin Omatako peaks, the Paresis and Erongo mountains. The Waterberg and Mount Etjo are flat plateau-type mountains. Towards the west, this old surface is characterised by more mountainous terrain with regular, generally westward-flowing rivers. While the Omatako Omuramba drains towards the east and finally to the north-east, the Ugab and several smaller rivers drain towards the west coast. Annual average rainfall decreases from a high of more than 400 mm in the east to below 50 mm west of the escarpment.

Geology

The area is situated in the centre of the Damara trough. Classical geosyncline sedimentation produced a thick pile of ill-sorted sediments, which form the Ugab and Khomas subgroups of the Swakop Group (Damara Sequence). On the platform edges of the trough chiefly calcareous sediments were deposited. Both rock suites


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Otjosongomingo (Kleiner Waterberg)

were subsequently folded and metamorphosed, and granitic intrusion took place. Bands of marble and quartzite in these otherwise phyllitic metamorphic rocks are of hydrogeological significance. The youngest intrusive rocks in the area are complexes of post-Karoo age like the Brandberg, Messum Crater in the Goboboseb Mountains, Paresis Mountain and scattered smaller outcrops.

Major north-east striking faults and thrusts, and north-striking faults form the present outcrop boundary of younger rocks mainly represented by aeolian sandstones of the Etjo Formation at the Waterberg and Mount Etjo. These sandstones overlie the argillaceous sediments of the Omingonde Formation, which dominate the geology between the farms Ohakaue in the north and Vrede in the south. To the west of the Otjiwarongo - Omaruru tar road, these young sedimentary rocks are absent, except for some outcrop of Karoo west of the Brandberg. Two bodies of older lavas and associated pyroclastics occur south-east of Khorixas, while basalt flows of Karoo age form the Goboboseb Mountains.

Hydrogeology

In the eastern part of the area, the Waterberg Plateau forms a major hydrogeological structure. Here, Etjo sandstone rests with an unconformity on the underlying Omingonde argillite, giving rise to a series of contact fountains that drain water from the porous sandstone. Owing to the general dip of the contact plane, springs emerge on the southern slope of the Waterberg and the northern edge of the Klein Waterberg. Although this gives the impression of an abundance of groundwater, this area generally has only moderate to poor groundwater potential. The springs collect groundwater over a large area of sandstone outcrop and concentrate the flow along a shallow contact zone. The tourist camp of Bernabé de la Bat receives spring water from these springs discharging some 3 m^3/h. The outflow is captured in a pit, and two thirds of the spring water is used by the resort while one third goes to a nearby farm house, leaving none to sustain what was once a productive wetland.


Jürgen Kirchner

Spring at Bernabé de la Bat, Waterberg

The Omingonde Formation generally has low groundwater potential owing to the argillaceous character of the rocks. Locally though, especially at contact zones towards intrusive dolerites, this can improve to moderate potential. Faults can also be good targets for exploration. A water scheme on the Omingonde Formation was established at the Omatako Dam (70) to supply operations personnel. The low-yielding boreholes supply Group B-D water. At the former Osire (78) police station, now a refugee camp, water is found in the Omingonde Formation, which is overlain by Kalahari sediments. The high water demand due to the increasing number of refugees is depleting the resources.

The groundwater potential of fractured aquifers in the Swakop Group of the Damara Sequence is generally low. However, the carbonates (marbles and limestones) are of moderate potential and at properly selected targets like fracture zones and karstified contact zones, even high yields can be found. This depends on the amount of rainfall and associated weathering and recharge. The most significant aquifer presently utilised is the marble aquifer north and north-east of Otjiwarongo (82). The water supply scheme relies on a fractured and slightly karstified marble band of the Karibib Formation, which allows medium to high pumping rates and supplies Group B water. The number of boreholes was increased to over 20 to keep up with the demand, and the scheme is spread over an area of 15 x 30 km.

The water supply scheme of Kalkfeld (40) is situated between Omaruru and Otjiwarongo in an area underlain by meta-sediments and granites of the Damara Sequence that have a low groundwater potential. A small dam was built to provide additional recharge to boreholes and a well. Some production boreholes were drilled on fractures intersecting marble bands, but their yields were low and the capacity of the water scheme is still lagging behind the demand. At Hochfeld (38), a small rural centre north-east of Okahandja, the groundwater from the two production boreholes is mainly used for the police station. The geology, undifferentiated Damara Sequence, is obscured by a surficial calcrete layer. There is an ephemeral pan nearby that appears to provide sufficient recharge of good quality water.

The intrusives, granites and lavas, inherently display poor water bearing characteristics. Locally, especially along riverbeds, drill sites can be determined quite successfully, but the reserves are mostly limited. F BOCKMÜHL

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Central Namib - Windhoek Area

The Central Namib - Windhoek region extends from Windhoek in the east to the Atlantic Ocean in the west. The Ugab and Kuiseb rivers form the northern and southern boundaries.

The most important towns are Windhoek, Walvis Bay and Swakopmund. Henties Bay is a tourist centre at the mouth of the Omaruru River north of Swakopmund. Further inland are Uis, a former tin mine, Okombahe and Omaruru. A village exists at the Spitzkoppe and a school settlement at Tubussis. Several towns are situated in the catchment of the Swakop and Khan rivers: Okahandja, Otjimbingwe, Karibib, Usakos and Arandis as well as the Rössing uranium mine. On the Kuiseb River upstream of Walvis Bay are several Topnaar settlements and the desert research station at Gobabeb.

Windhoek is the administrative and industrial centre of the country and the only town with more than 200 000 inhabitants. The main economic activities in the central and coastal area are light industry, farming, fishing, mining and tourism. Cattle are raised in the Windhoek, Okahandja and Omaruru districts. There is some small-scale irrigated agriculture on the banks of some rivers and extensive small stock farming alongside these ephemeral rivercourses and on the edge of the Namib Desert.

Geomorphology

Windhoek is situated in a valley surrounded by the Auas, Eros and Otjihavera mountains, which form the country's central watershed from where large river systems radiate in all directions. The Swakop and Kuiseb rivers flow to the north and west, while the Oanob drains to the south and the Nossob and Olifants to the east. The Windhoek valley is a geological graben structure bounded by north-south striking fault systems in the east and west.

The Khomas Hochland is a deeply dissected mountainland of intermediate elevation, where the geomorphology is closely related to the underlying geology. The fracture pattern of the Kuiseb schist determines the direction of the drainage system. The area has a thin soil cover and supports a thornbush savanna, which is ideal for cattle ranching. West-flowing rivers have carved deep gorges (e.g. Kuiseb canyon) across the Khomas Hochland, especially where they break through the Great Escarpment.

The central part of the Namib Desert is characterised by gravel plains and rocky outcrops. The dune field along the coast between Swakopmund and Walvis Bay is an extension of the Namib sand sea. Morphologically, the Central Namib is a steeply inclined plain, rising from sea level to 1 000 m in less than 100 km. There is a conspicuous gap in the Great Escarpment in this area and in its place are isolated mountains and inselbergs like the Erongo, Spitzkoppe and Brandberg. Soils are absent on rocky slopes, which are often covered with weathered material, while the soils of the Namib gravel plains are generally rich in gypsum. Calcretes cover a large part of the transition zone between desert and savanna.

Geology

The geology of the central region is dominated by the

Damara Sequence. This sequence underlies most of central and northern Namibia. The basal arenitic succession of the Nosib Group was laid down between 850 and 700 million years (Ma) ago. Widespread carbonate deposition followed (Swakop Group) and interbedded mica and graphite schist, quartzite, massflow deposits, lavas and iron formation point to fairly variable depositional conditions south of a stable platform where only carbonates occur (Otavi Group, see Otavi Mountain Land or Karstland). Near the southern margin of the Damara orogen deep-water fans of the Auas Formation were deposited. These rocks are overlain by thick schists of the Kuiseb Formation, which contains a narrow 350 km long zone of interbedded oceanic amphibolites, the Matchless Member. The latter often contains massive sulphide orebodies (e.g. at Otjihase and Matchless mines).

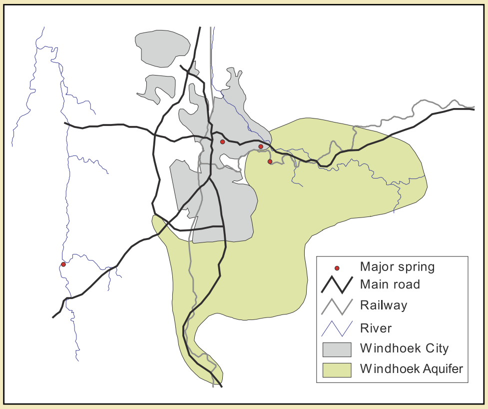
Deformation, apparently as a consequence of continental collision some 650 Ma ago, was accompanied by syntectonic intrusion of serpentinites along the southern margin and syn- to post-tectonic granites. Alaskite (a type of pegmatitic granite) emplaced at deep stratigraphic levels contains uranium mineralisation at the Rössing Mine. Tin-bearing pegmatites occur at higher levels in the Uis area. Pegmatites can also carry lithium, beryl, tantalite and gemstones (Karibib, Usakos and Spitzkoppe). Hydrothermal tin, tungsten, base metal and gold mineralisation occur at many places, for instance at the Brandberg West and Navachab mines.

There is a large gap in the geological history of the central area after the Damara orogenesis. Sediments of the Karoo Sequence were deposited and largely eroded afterwards, except for some remnants preserved under volcanic rocks. In the early Cretaceous, the continental break up of South America and Africa caused widespread volcanic activity. From 180 to 120 Ma ago, basaltic lava erupted from deep-seated fissures and covered large parts of Namibia. Erosion has removed most of these sheet basalts, but their feeder channels are still present in the form of dolerite dykes (dolerite is a coarse-grained basalt). The NNE striking dykes are found throughout the Namib Desert. An example of the original sheet basalts is the Etendeka Plateau north of Swakopmund.

The basaltic volcanism in the central Namib was accompanied by partial melting of Damara Sequence meta-

An overview of the Windhoek city water supply

Windhoek owes its existence to the presence of springs, which provided an ample supply of water when the area was first settled. The map below shows the position of springs and the Windhoek aquifer. The mostly thermal springs emerged from deep-seated faults in quartzites that form the main aquifer. The spring water contained traces of hydrogen sulphide and high concentrations of salts (890 mg/L total dissolved solids, TDS).



Map of Windhoek city and aquifer

The springs dried up when pumping of groundwater from boreholes started in the 1920s. The wellfield currently consists of approximately 50 boreholes and contributes about 10 % of the city's total water supply. Another 10 % is provided by wastewater reclamation, but most of the town's water comes from a surface water supply scheme consisting of three interconnected dams. The table shows the supply capacity of Windhoek's water sources. The current water use of 20 Mm^3/a matches the supply and the only spare capacity is provided by wastewater treatment at the Goreangab water reclamation plant. This plant was built in 1968 and upgraded from 8 000 m^3/day

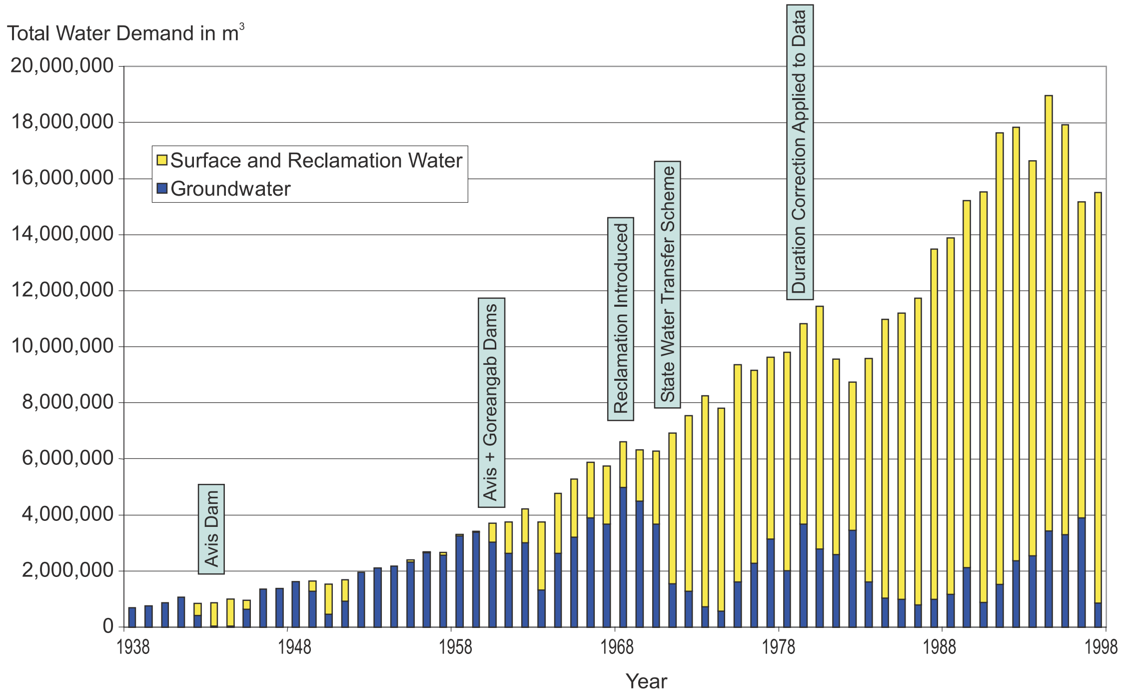
to 21 000 m^3/day in 2000. Windhoek was one of the first cities in the world to introduce direct recycling of effluent for drinking purposes. Purified effluent is also provided to consumers for landscape gardening.

Source	**Supply capacity (Mm^3/a)**
Von Bach, Swakoppoort and Omatako dams	17.0
Avis & Goreangab dams	1.1
Windhoek wellfield	1.9
Total	**20.0**

The history of Windhoek's water supply highlights the efforts required to sustain a population growth centre in an arid country like Namibia. When local sources like springs, boreholes, surface water (Avis and Goreangab dams) and even treated wastewater became insufficient to meet the ever increasing demand, additional sources, had to be found further and further from Windhoek. The Von Bach and Swakoppoort dams were built on the Swakop River near Okahandja, while the Omatako Dam is over 150 km away. Later the option of supplying water from the Otavi Mountain Land near Grootfontein was added (see Eastern National Water Carrier - ENWC), and a possible future proposal to secure the capital's water supply would be a pipeline linking the Okavango River to the ENWC.

All these developments took place during a time when water authorities pursued a policy of unlimited water supply at low cost to the consumer. This policy was first revised in the 1990s when efforts were made to curb waste and limit supply to a "reasonable" demand. The Windhoek municipality introduced water demand management in 1994.

The strategy concentrates on changing consumer habits by increasing public awareness on the importance of water saving and the implementation of a block tariff system with a steeply rising water cost with increasing consumption. Some other measures include the reduction of residential plot sizes, implementation of legislation to address water conservation in Windhoek, improved maintenance and technical measures to reduce leaks. This led to a water saving of 1.2 Mm^3 in 1999.



Source: SCANDIA Consult & INTERCONSULT

Windhoek's historical water consumption

The success of water demand management shows a remarkable reduction in the water consumption in the late 1990s. In 1997, the total water use was equivalent to that of 1990, despite a 45 % population increase. If Windhoek sustains water demand management successfully, savings of up to 18 Mm^3 can be expected in 2010 compared to the unrestricted water demand. This would delay the need for a pipeline scheme from the Okavango River and allow time for an ecological impact study.

A new system of artificially recharging the Windhoek aquifer has recently been tested. Treated water from Von Bach Dam is pumped into the Windhoek production boreholes and stored underground to reduce water losses from evaporation. Many years of abstraction from the wellfield have lowered the water table, creating enough open pore space to allow infiltration of up to 50 Mm^3 of water when the dams are sufficiently full. This water can be recovered when water shortages occur. Once this scheme becomes operational, the Windhoek aquifer will play an important role in securing the city's water supply, but will have to be conscientiously guarded against pollution.

Currently the most vulnerable part of the aquifer is threatened by residential and industrial development. Effluents from textile industries for instance, can cause extremely serious, often irreversible groundwater pollution.

J KIRCHNER, A VAN WYK

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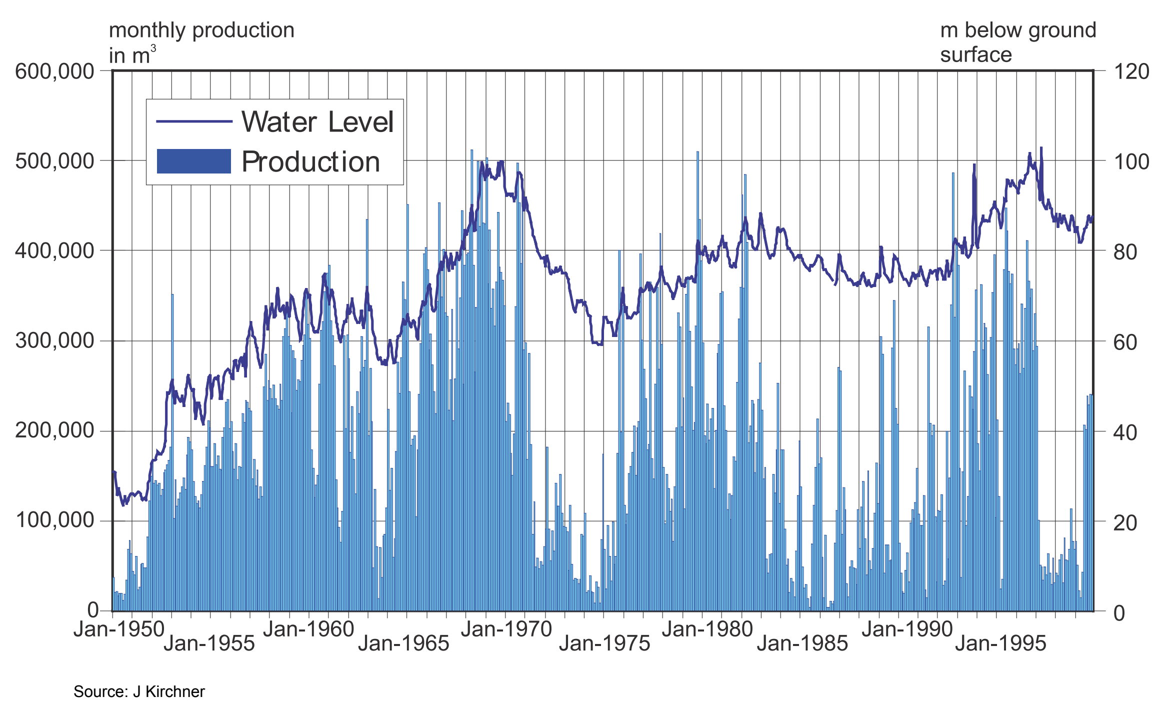


Source: J Kirchner

Production and water levels in the Windhoek aquifer morphites, which produced granitic or granodioritic rocks. These intrusions formed ring complexes such as the Erongo Mountains, Spitzkoppe and Brandberg. The Erongo is a composite magmatic complex consisting of a lower basalt layer (part of the sheet basalts) overlain by granodioritic/ rhyolitic volcanics and intruded by younger Erongo granite.

The granites of the Erongo, Brandberg and Spitzkoppe intruded into the earth crust, but later erosion removed the surrounding rocks and left the harder granites towering over the plains. The Namib was uplifted rapidly by epirogenic forces and subjected to considerable erosion (possibly 2-3 km) in the early Cretaceous (120-100 Ma ago).

The erosion phase was terminated by a change in climate from humid to arid. The oldest Tertiary sediments are reddish, semi-consolidated, sandstones of the Tsondab Formation that were originally windblown dune-sands. A slightly wetter climate caused the deposition of conglomerates and gravels in the broad valleys of precursors to the present west-flowing rivers. This formation is known as Karpfenkliff conglomerate in the Kuiseb valley.

Both Tsondab Sandstone and the younger gravels are capped by pedogenic calcretes, which were formed during a long period of semi-arid climate and tectonic stability. A renewed uplifting phase in the late Tertiary caused the incision of the major rivers in the Namib. The Oswater conglomerate was formed in the newly incised Kuiseb canyon.

Periods of erosion and sedimentation under varying climatic conditions created terraces with remnants of gravel, sand or silt deposits throughout the late Tertiary and Pleistocene. Short-lived wetter intervals gave rise to local pan carbonates and spring tufa deposits.

Hydrogeology

The fact that most towns in the western Central Region are situated on or near rivers is a reflection of groundwater availability in the area. Sufficient water for larger settlements can only be obtained by surface water storage in dams or from alluvial aquifers, while the potential of bedrock aquifers is very limited. This is partly due to the low rainfall and lack of recharge, and partly to the generally unfavourable aquifer properties of Damara Sequence rocks.

Only the quartzite aquifer in the Windhoek area can be classified as high yielding. The Windhoek aquifer is developed in an area that exhibits numerous north to north-west striking faults and extensive jointing. The high yields of the Auas quartzites are due to secondary porosity derived from brittle deformation, while the interbedded schist layers were more susceptible to plastic deformation. The primary porosity and hydraulic conductivity of both quartzite and schist are negligible. The faults associated with the development of the Windhoek graben are generally north-south subvertical tension faults. They form the major water conductors in the Windhoek area and extend as a zone of moderate potential northward towards Okahandja. Equally moderate yields are found in the Auas quartzites south-west and north-east of Windhoek.

The Windhoek aquifer is recharged mainly by direct infiltration of rainwater over areas of quartzite outcrop. In areas underlain by schist, direct recharge is possible along fault zones. The presence of strong flows of hot water in fault zones some 3 to 4 km north of the main quartzite outcrop area indicates deep groundwater circulation. The mean age of water pumped from Windhoek boreholes is approximately 12 000 years. Boreholes close to the Avis Dam receive indirect recharge when the dam contains water (see Box on "An overview of the Windhoek city water supply").

The Khomas Hochland situated between the Kuiseb and Swakop rivers is underlain by mica schist with occasional quartzite intercalations. Higher rainfall east of Windhoek leads to enhanced chemical weathering of the schist and thus less recharge, while joints and fractures in the Khomas Highland tend to be open. The prevailing fracture directions are north-south, north-west and north-east. Mean borehole yields of about 2.4 m^3/h are encountered east of Windhoek, 9 m^3/h in Windhoek and 2.9 m^3/h further west. Borehole success rates and yields decrease towards the Namib.

Main targets for geological site selection are steeply dipping north-south trending fractures and joint zones, if possible in competent rocks, although feldspathic quartzites should be avoided. Farm dams in the vicinity have a noticeable influence on borehole yields as long as they contain water. Thus it is standard practice to site boreholes near dams to render the supply more reliable. Marble bands also have a comparatively good yield potential. Near Okahandja, subvertical pegmatite dykes parallel to the strike of the mica schist are preferred drilling targets. Borehole sites should be selected to intersect these structures and contacts between 15 and 35 m below the water level, higher up and lower down, borehole yields tend to decrease. The small water scheme at Ovitoto near Okahandja draws water from an aquifer in fractured Kuiseb schist. Its original intermediate yield has decreased due to over-abstraction and lack of recharge.

Moderate yields are also encountered in the marble and schist aquifers around Karibib and the calcrete aquifer in the Kranzberg area at Usakos. But while the marbles supply the much larger town of Otjiwarongo further north, the recharge at Karibib is insufficient to maintain the required yields, and the water supply to the town and Navachab gold mine is augmented by the Swakoppoort Dam.

Other bedrock aquifers in the eastern part of the Namib, e.g. in the former Damaraland, are barely able to supply enough water for stock watering. A large number of dry boreholes were drilled in this area. The yield potential is generally low, but locally moderate. Yields decrease to very low and limited in the Namib. Groundwater in fractured aquifers between the coast and 20-150 km inland is mostly saline as indicated by orange hatching on the Map. Fractured aquifers with inadequate yields are used at the Spitzkoppe (94) and Tubussis (101) water supply schemes. The Spitzkoppe is a popular tourist attraction in the Erongo Region. The mountain consists of granite intruded into meta-sediments of the Swakop Group. A settlement established at the foot of the mountain depends mainly on tourism and some small stock farming. The water scheme's boreholes are sited on fractures intersecting the small Spitzkoppe River. Their yields are low, recharge is erratic and its absence leads to poor water quality of Group C-D. A treatment plant to improve water for domestic consumption has recently been built.

The westward-flowing rivers are life-sustaining oases in the Namib Desert. The sand, gravel and silt deposits in the riverbeds are usually 10-30 m thick and have moderate to high yields. On the Map the alluvial aquifers are indicated by light and dark blue lines slightly wider than the riverbeds. Care should be taken that these aquifers are not depleted, as a certain degree of irreversible compaction of the alluvium may result in loss of open pore space. Irregular rainfall events produce fine sediments that are transported during intermittent floods and deposited in layers and lenses throughout the alluvial riverbeds. These clayey layers, once saturated, can act as a barrier, preventing water from reaching the lower portions of the aquifer during flood events. The following text describes the rivers from north to south and gives details on the associated water supply schemes.

Ugab River: There is very little development on the lower Ugab River and the only water scheme in the area is at Anichab (5), an educational centre with schools and hostels. The alluvium in the river is shallow (10-15 m) and very dependent on regular recharge. The Ugab used to flow most years, but increasing water use in the upper catchment has reduced the number and volume of floods passing Anichab.

Wilhelm Struckmeier

The alluvial aquifer at Nei-Neis

Omaruru River: Omaruru is one of the municipalities that run their own water supply scheme. All groundwater for the town as well as for extensive private irrigation schemes on smallholdings east of the town, is pumped from the extended alluvial plain of the Omaruru River. The strip of land along the river between the Etjo Mountains and Okombahe is a water control area where water quotas are allocated to users by the Department of Water Affairs according to a permit system.

Further downstream at Okombahe, a dolerite dyke cuts across the Omaruru River forming a barrier that forces groundwater to the surface. A wellfield is situated upstream

The Omaruru Delta (Omdel) scheme

This important water scheme (72) is located in the Omaruru Delta (Omdel) north-east of Henties Bay. In this area, a precursor of the Omaruru River has incised paleochannels up to 120 m deep, which were later filled with sediments. The Omdel wellfield of 33 boreholes was developed in the late 1970s to augment coastal supplies from the Kuiseb River wellfield due to growing water demand in the region.

The aquifer is found in the deeply incised main channel, which is flanked by the southern elevated channel and northern elevated channel as well as northern channel system. The water in the main channel is fresh to slightly brackish, while both elevated and northern elevated channels contain older saline groundwater.

The alluvium consists of a lower succession of coarse sand and gravel overlain by a semi-confining unit of calcareous silt to fine sand, which is topped by another sand and gravel layer. The lower coarse unit is the main water source and heavy abstraction has drawn the water table down below the fine layer. The last significant recharge event occurred in 1985.

The Omdel Dam and artificial recharge scheme was built to increase the sustainable yield of the aquifer from 4.5 to 8.2 Mm^3/a. The Omdel Dam was completed in 1994 and has a capacity of 40 Mm^3. Its purpose is to catch floodwater, which is released downstream of the dam wall after the silt has settled out. The clear water flows 6 km as surface flow to an infiltration basin. The water infiltrates down to the aquifer where it is protected from evaporation and available for abstraction from the existing production boreholes.

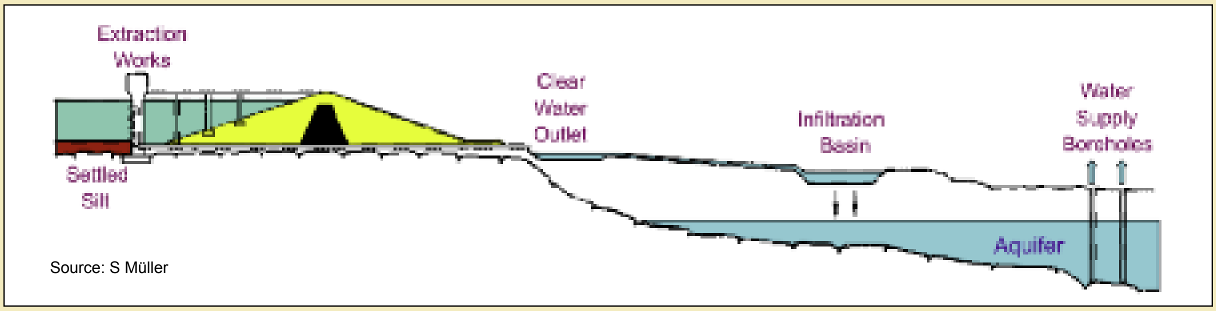
S MÜLLER

Diether Plöthner

The Omdel Dam

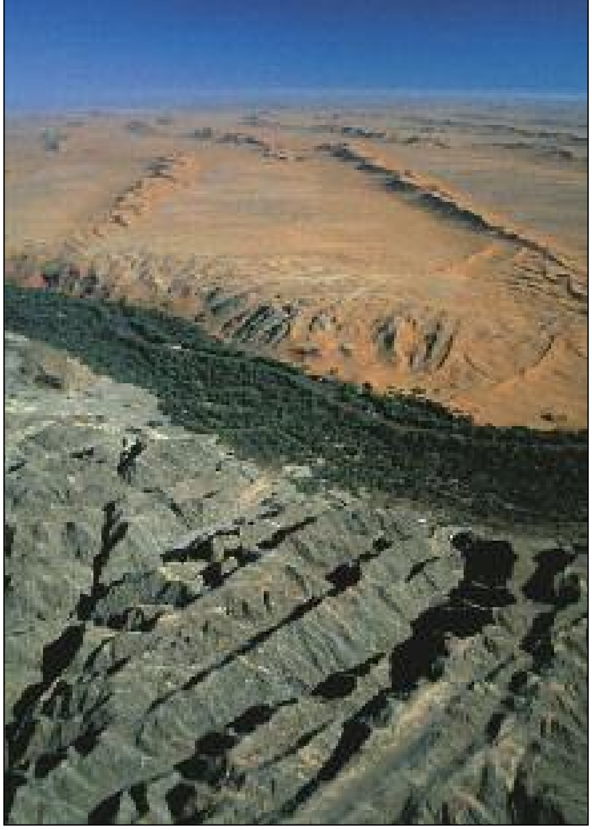
Wilhelm Struckmeier

The Omdel infiltration basin



Source: S Müller

Cross-section of the Omdel Dam scheme



Wynand du Plessis

The Kuiseb River forms the boundary

of the barrier on 10-20 m thick alluvium with very high yields and regular recharge. The alluvial aquifer at Nei-Neis (62) is used to supply the town of Uis 30 km north-west, where a tin mine was in operation until the early 1990s. The wellfield consists of 10 boreholes spread out over several kilometres.

While the Omaruru River flows almost every year at Omaruru and Okombahe, floods become less frequent further downstream due to infiltration losses. The sustainable yield of the aquifer was at times insufficient for the mine's demand, but is more than adequate for the presently reduced consumption rates.

Swakop River: The Swakop and its tributary, the Khan River, supply groundwater to several towns in the central area. Okahandja obtained water from a tributary of the Swakop, the Okahandja River, in the past, but switched to surface water supply from the Von Bach Dam in the 1970s. Otjimbingwe (80) used springs and shallow wells in the Swakop River during colonial times. The water supply situation changed drastically after the construction of the Von Bach and Swakoppoort dams upstream of Otjimbingwe. Floods were much reduced in frequency and volume, so that recharge to the borehole scheme was sometimes insufficient to meet the demand. As the Swakop River enters the Namib Desert, its groundwater becomes gradually more saline and generally unsuitable for human consumption. Consequently Swakopmund's water supply comes from the Central Namib water supply scheme (see Box on "The Kuiseb dune area investigation").

The wellfield at Spes Bona (44) on the Khan River 20 km north of Karibib is unusual because the production boreholes draw water from both alluvium and underlying highly fractured and weathered bedrock (mostly limestone and shale of the Damara Sequence). The water scheme was mothballed when Karibib was linked by pipeline to the Swakoppoort Dam. Usakos obtains groundwater from the Khan River and its tributary, the Aroab River (also called Kranzberg River). There are two large-diameter wells in the Khan River and several boreholes on an extensive calcrete terrace recharged by the Aroab River. The groundwater in the Khan River becomes brackish downstream of Usakos. It is used at the Rössing uranium mine for industrial purposes, reducing the mine's reliance on freshwater from the Kuiseb and Omdel aquifers.

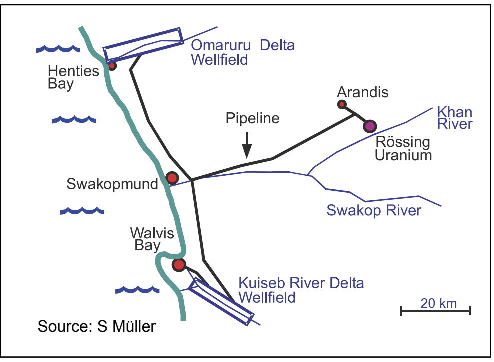
Kuiseb River: The Kuiseb River forms the boundary between the gravel plains of the Central Namib and the southern Namib sand sea. Gobabeb, a desert research station on the lower Kuiseb River, currently receives freshwater by water tanker. Boreholes placed on the banks of the river supply a mixture of Kuiseb water and saline water discharging from the desert. Between Gobabeb and the water supply schemes near Walvis Bay, several Topnaar settlements abstract groundwater from dug wells in the Kuiseb River.

The alluvial aquifer in the lower part of the Kuiseb River at Rooibank (52) has been used since 1923 to supply water to Walvis Bay. In 1966, the Rooibank B Area was developed and in 1992 an additional wellfield at Dorop South, closer to the coast, came into operation. Another wellfield was established at Swartbank upstream of Rooibank in 1974 to supply Swakopmund and Rössing Mine. In addition to 53 boreholes in the Kuiseb wellfields, there is one large-diameter, horizontal filter well (Fehlmann well).

The alluvium in the Kuiseb River is 15-20 m thick. Its relatively high permeability allows high pumping rates and quick recharge in case of floods. The sustainable yield of the aquifer was however over-estimated in the 1970s as 11 Mm^3/a. This figure was revised to a more realistic 4.5 Mm^3/a in the 1990s.

Central Namib water supply scheme

Walvis Bay, Swakopmund, Rössing Mine and Henties Bay obtain freshwater from the Central Namib Water Supply Scheme based at Swakopmund. The scheme is run by NamWater and draws groundwater from wellfields in the Omaruru and Kuiseb rivers, which are the nearest sources of potable water.



Source: S Müller

Wellfields and pipeline network of the coastal area

In the past Swakopmund and Rössing were supplied from the Kuiseb River, but in 1979 the Omdel scheme was added to augment the resources. The map shows the wellfields and pipeline network.

The historical water consumption of the coastal area since 1970 is shown in the graph below. While Swakopmund's water demand has increased from 1-2.5 Mm³/a and Walvis Bay's from 3-5 Mm³/a, Rössing Mine (RUL) has reduced its water consumption from 10 to 2-3 Mm³/a after the implementation of water recycling (75 % of the total water used) and augmentation of supplies with brackish water from the Khan River (3 %) in 1980. The mine's freshwater demand is currently only about 2 Mm³/a (22 %).

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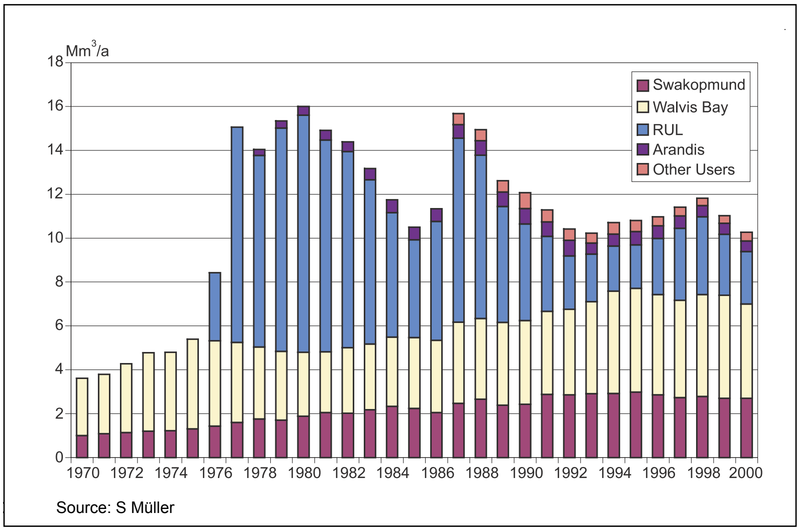

Source: S Müller

The historical water consumption of the coastal area since 1970

The Kuiseb dune area investigation

The geophysical investigation of the area under the dunes south of the Kuiseb River traced the channels created by the Kuiseb River while gradually shifting its course northwards. The river mouth was previously at Sandwich Harbour where freshwater springs still occur today. The area was studied as a potential water source for Walvis Bay and although the aquifer characteristics, recharge and quality may be poor, promising targets for expanding the wellfield were identified. Access in some cases remains a problem.

Dieter Plöthner

The dunes south of the Kuiseb River

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Hochfeld-Dordabis-Gobabis Area

The Hochfeld-Dordabis-Gobabis groundwater area stretches from east of Windhoek to the eastern border of Namibia. It mainly includes sandveld between the Kalahari basins of northern Omaheke-Epukiro and the Stampriet artesian basin. The Namibian section of the Trans-Kalahari Highway connects Windhoek with towns and villages like Seeis, Witvlei, Gobabis and the Buitepos border post.

The eastern Khomas Region, up to the Hosea Kutako International Airport, is mountainous, drained in an easterly and south-easterly direction by the ephemeral Seeis, White Nossob and Black Nossob rivers that originate in the highlands to the east of Windhoek and Okahandja. The area is characterised by tree savanna and rich grasslands, which support a thriving cattle industry.

Geology

This area has a complex geology and structure. The oldest rocks are Mokolian intrusives. Other pre-Damara metamorphic and intrusive formations belong to the Sinclair and Rehoboth sequences as well as the Abbabis and Hohewarte Metamorphic Complexes. Damara Sequence however predominates in the area and consists mostly of Khomas rocks with Kuiseb Formation quartz-biotite schists, interbedded marble, amphibolite (Matchless Suite) and amphibolite schists. The Hakos Group shows similar lithologies with notable exception of the Auas and Otjivero quartzites and Corona marbles at the base of the group. The Nosib Group mainly consists of arenitic rocks like sandstones, quartzites, conglomerates and subordinate schists. The eastern half of the area is dominated by rocks belonging to the Nosib Group, with outcrops of Nama Group sedimentary rocks filling synclines.

Hydrogeology

Both alluvial and fractured aquifers occur in the area east of Windhoek. Alluvial aquifers are found along the riverbeds of the Seeis River and along most of the course of the White Nossob. The Seeis water supply scheme (92) provides the local police station with water and was later expanded to also supply the Hosea Kutako International Airport, 10 km to the west. The alluvium although only 10-15 m thick, allows rather high abstraction rates. This moderate potential, porous aquifer is easily and regularly recharged by frequent floods in the Seeis River. The Seeis wellfield supplements the Ondekaremba water scheme (74) established to supply the international airport. The boreholes at Ondekaremba are on a fractured marble and quartzite aquifer of the Auas Formation (Khomas Subgroup) recharged by the Seeis River.

Farms along the White Nossob River used to have a plentiful water supply from the alluvial aquifer. This changed drastically after the construction of the Otjivero Dam. The aquifer immediately downstream of the dam wall is now practically dry due to a lack of recharge. Upstream of the dam, water is still abstracted from high-yielding wells and boreholes.

DWA Archive

The Otjivero Dam main wall under construction

A porous aquifer exists north-east of Gobabis where Kalahari sediments overlie quartzites. Correctly sited drilling targets can tap a combination of primary porous and secondary fractured aquifers.

Most of the groundwater basin is underlain by either schist or sandstone/quartzite, which have inherently different water bearing characteristics. Generally, groundwater in these fractured aquifers is hosted in faults and other secondary structures, more prevalent in competent rocks like sandstone and quartzite. In addition, schist weathers faster leaving a clayey residue in faults and fractures. As weathering progresses from the surface downwards, weathered fault zones at the surface are poor aquifers, but deeper intersection of faults can result in higher yields. For example on the farms Apex and Aurora, on the road between Omitara and Steinhausen, water strikes at 60 m and 120 m below the ground level had yields of over 10 m^3/h.

Selecting drill sites for such deep intersections is however difficult as the structures are usually narrow and the (mostly steep) dip of the fractures is difficult to determine accurately. In the quartzitic sandstone terrain, selecting drilling targets is not as difficult, provided that the geohydrological conditions are correctly interpreted and the appropriate geophysical investigations are conducted. This was proven by a recent investigation in the vicinity of Gobabis (see Box on "Gobabis water supply").

The water scheme for the village of Witvlei (104) draws water from fractured limestone of the Kamtsas Formation (Damara Sequence) along the White Nossob River. The river provides recharge ensuring a plentiful groundwater supply. Further east of Gobabis three small water supply schemes are situated on slightly fractured low-yielding quartzite aquifers of the Kamtsas formation: Ernst Meyer school (25), Buitepos border post (18) and Rietfontein (86). The latter scheme supplies a number of farming communities along the Rietfontein River near the Botswanan border (ENE of Gobabis). The borehole yields are low to moderate and insufficient to meet the rising demand. Over-abstraction has caused a change in water quality from Group B to C.

Another water scheme on Damara Sequence rocks is Oamites (65) north of Rehoboth, formerly a mine, now used as an army camp. The aquifer is fractured marble of the Swakop Subgroup. There is one strong production borehole at the camp and two on the farm Nauaspoort alongside the Usip River.

The meta-sediments of the Rehoboth Sequence are generally low-yielding aquifers, e. g. at Kwakwas (53), a small water scheme north-west of Rehoboth where wind pumps are used to abstract small volumes of groundwater. Yet locally, moderate yields are found in fractured quartzites of the Rehoboth Sequence, for instance at Dordabis (22) south-east of Windhoek. The boreholes receive recharge from the Skaap River. Recently the scheme was extended by two new boreholes to meet the rising demand.

An interesting situation exists on the farms Owingi,

Gobabis water supply

Originally Gobabis (32) obtained water from boreholes within the town and townlands. Later the scheme was extended to the Witvlei area and the White Nossob.

More recently the Otjivero Dam was constructed to assure a more permanent water supply for Gobabis. The borehole schemes at South Station and Grünental were then rested. Due to inconsistent rainfall, however, the dam was dry for several seasons in the early 1990s and a hydrogeological investigation for additional boreholes started in 1995. The old boreholes were also re-evaluated and following a detailed investigation a new wellfield of eight boreholes was established north-east of the town, close to the Black Nossob River. Fractured aquifers were identified in the basement and porous aquifers in saturated Kalahari sediments. These can form a combined aquifer system in some places.

The geology in the Gobabis area is made up of Kamtsas quartzite (Damara Sequence) and sediments of the Kuibis Subgroup (Nama Group), locally overlain by tillite and shale of the Dwyka Formation (Karoo Sequence). The fractured aquifers tapped by the various wellfields have moderate to high yields and receive fairly regular recharge.

Drilling targets were selected geophysically, employing electrical resistivity and electromagnetic methods. Drilling results proved the value of appropriate scientific investigation methods. Thirty-six boreholes were drilled of which 61 % had yields of over 10 m^3/h, 10 produced less than 10 m^3/h (28 %) and only 4 were dry (11 %).

Considering previous water shortages and the prevailing drought this investigation was highly successful.

F BOCKMÜHL

Conellan and a portion of the farm Tokat, some 60 km north of Gobabis. A gravelly and calcareous porous Kalahari aquifer overlies basement consisting of undifferentiated sedimentary, volcanic and metamorphic rocks of the Eskadron Formation, Sinclair Sequence. Farmers in the area regularly report that if boreholes are drilled "too deeply", the water from the upper aquifer drains away into the lower formations. This is inferred from a rushing sound likened to flowing water in the borehole.

A possible explanation for this phenomenon was found when borehole WW35206 was drilled in this area under professional supervision. A blow test yield of 7.6 m^3/h was recorded in the Kalahari aquifer. This yield drastically increased to over 100 m^3/h when aquifers in the basement were intersected. After drilling, the water level in this borehole is 0.15 m below surface, much higher than the normal Kalahari aquifer water levels. This indicates that the basement aquifer is under pressure and thus at least sub-artesian. With effective sealing of the Kalahari aquifer, proper artesian conditions are likely. As with many aquifers under pressure, gas release takes place once the confining horizon has been punctured. This gives rise to a rushing sound, which could explain the farmer's observation of water "draining away". F BOCKMÜHL

Stampriet Artesian Basin

The Stampriet Subterranean Water Control Area, as defined by law in the Artesian Water Control Ordinance of 1955, lies in the south-eastern part of Namibia roughly between 23° and 26°S; 17°30' and 20°E, the Botswanan border.

Its northern boundary is defined by sub-outcrops of Karoo strata. In the north-west an arbitrary margin (following the railway line) delineates the area where sandstones with artesian groundwater might still be encountered under the Kalkrand Basalt. In the west the basin is limited by the escarpment of the Weissrand Plateau that rests on Nama Group sediments. The southern boundary is a line south of which no (sub)artesian conditions exist. Eastwards the Stampriet Artesian Basin extends some limited distance beyond the Namibian border into Botswana and South Africa.

Geography and geomorphology

In the west, the Stampriet Artesian Basin is bounded by the Weissrand, a surface limestone plateau that rises 80 m above the Fish River plain. A dune field commences west of the Auob River and stretches eastwards to beyond the Nossob River. These stationary longitudinal dunes are nearly parallel to the river system and about 10 to 15 m high. The grass covered dune valleys in between are several hundred metres wide. In the north a gradual transition to comparatively monotonous sand or calcrete plains is followed by the first north north-east trending quartzite ridges of the central highland.

The area receives between 150 and 250 mm of rain per annum. Potential evaporation is as high as 3 800 mm in the south-eastern part of the basin, and in normal years little or no local runoff is generated. The Auob River below Stampriet and the Nossob River from Leonardville to Aranos, are evidence of a much wetter climate in the past. The valleys are several hundred metres wide and sometimes incised more than 50 m into the Kalahari. The present rivercourses are generally little more than 10 m-wide and only about 1.5 m deep in occasional gullies. The Auob River is cut off from its upper tributaries by a dune field east of Kalkrand that blocks the Oanob and Skaap rivers. Downstream of the Auob and Nossob confluence with the Molopo River, recent

Jürgen Kirchner

Mukorob shale, between Nossob and Auob

Previous and recent investigations

In the beginning of the 20th century Dr H Lotz and Dr P Range were the first geologists responsible for the German Governmental Drilling Section developing groundwater resources in southern Namibia.

Range recognised the artesian conditions in the Stampriet Artesian Basin in 1906 when he sited a number of boreholes in the Auob and Nossob valleys. His publications on the results of his hydrogeological investigations in the area include detailed drilling records of the hundreds of holes drilled by Bohrkolonne Süd, and a wide-range of geological issues, including a resumé of the findings of the early explorers. Soon after World War I, the then Irrigation Department of the South West Africa Administration, launched an extensive drilling program in the area to develop new farmland for war veterans, a process that was repeated (here and in other parts of Namibia) after World War II. Borehole logs of these holes are filed under the borehole completion forms of the Department of Water Affairs (DWA). Some of the old information is kept in the Geohydrology library of the DWA. The wealth of archive documents stored in the National Archives is difficult to access.

P Range produced the first geological map of the artesian basin in 1914

After World War II, the SWA Administration employed Dr Henno Martin as Head of the Geological Survey. Under his supervision groundwater exploration took place in the still undeveloped parts of the Stampriet Basin. Borehole completion forms of holes sited and described by him form the basis of the knowledge of the Basin. Martin drew a large number of cross-sections based on these logs, most of them for the Coal Commission Report that looked into the coal-bearing properties of the Karoo Sequence.

During 1965, the Committee for Water Research of the SWA Administration identified an area east of Kalkrand as a problem area, due to the saline groundwater and the Regional Office of the CSIR in Windhoek was commissioned to investigate the groundwater quality there. This was the beginning of the Water Quality Map Project. Over a period of 12 years (1969-1981) nearly 30 000 groundwater samples from boreholes, wells and springs were collected in the country and analysed. Information about the farms, the boreholes and on water-related health aspects was also gathered. The results were presented in 25 reports and finally consolidated in four maps showing the total dissolved solids, sulphate, nitrate and fluoride concentrations at a scale of 1:1 000 000. At the same time, the Geological Survey investigated the geology and was responsible for the hydrogeological assessment of drilling applications in the Stampriet Artesian Basin, and collected isotopic data. Stratigraphic information is contained in reports that deal with exploration boreholes drilled for petroleum (to a depth of 1 000 m in 1965) and coal exploration (during the 1980s).

During the second half of the seventies, the Geohydrology department of the DWA became responsible for the Stampriet Artesian Basin. In the eighties, they conducted detailed investigations in the northern and northwestern parts of the basin and started collecting abstraction data. A major development project, in cooperation with the Japanese Government that aims at establishing a groundwater management plan to optimally utilise the groundwater resources of the basin is nearly complete. Concurrently the International Atomic Energy Agency is funding an investigation of recharge into the basin.

dune fields cut off the Molopo from the Orange River.

Economic activities in the area concentrate on stock farming, predominantly karakul breeding in the past, now diversified to include sheep, cattle and ostrich farming. In recent years, irrigation farming increased as electrification improved.

Longitudinal dunes after heavy rains

Geology and hydrogeology

There is a comparatively good understanding of the geology and hydrogeology of this aquifer system in Namibia. Groundwater occurs in the Nossob and Auob sandstones of the Ecca Group (lower Karoo Sequence), which are divided by shale layers and overlain by Rietmond shale and sandstone. Younger Kalkrand Basalt occurs in the north-west and Kalahari Sequence deposits. Predominantly calcrete and dune sand, cover virtually the entire surface of the Stampriet Artesian Basin. Several springs are located in the eastern outcrop area of the basalt. The Karoo succession rests unconformably on Kamtsas Formation in the north and north-west and on Nama Group rocks in the remainder of the basin. Sediment transport came from the north-east. The sandstones, in particular, were deposited in a deltaic environment. The dip of the Karoo formations is slightly towards the south-east (about 3 degrees) and the groundwater flow generally follows that direction.

Before the deposition of the Kalahari layers, a major river system entered Namibia at about 24° S and 20° E. This river flowed in a south-westerly direction, turning east of Gochas towards the Mata Mata area at the South African border. A major tributary from the north joined the main river at about 24° 45' S and just east of 19° E. This river system cut deeply into the Karoo Sequence, in places right down to the base of the Auob. Along the northern and western boundary of the basin the Kalahari cover is thin with calcrete or dune-sand at the surface. South-eastwards it reaches a thickness of 150 m, but in the pre-Kalahari river mentioned it can exceed 250 m in thickness. In the central parts the Kalahari consists mainly of fine sand, silt and clayey deposits. Consequently, with low rainfall, high potential evaporation and no runoff outside the Auob and Nossob valley, salts accumulate in the Kalahari and the groundwater quality deteriorates in a south-easterly direction. Because the confining layers and the Auob aquifer are largely removed in the pre-Kalahari valley, the quality of the groundwater in the Auob aquifer is also affected south-east of that valley and that part of the Stampriet Artesian Basin is called the "Saltblock".

Groundwater occurs in the Kalahari layers, in Kalkrand Basalt in the north-west, and in the Prince Albert Formation of the Karoo Sequence. Not all aquifers occur everywhere and the use of the aquifers is determined by water quality, depth to the aquifer, and their yields. Namibia, Botswana and South Africa share the artesian aquifers although they are predominantly used in Namibia where they are recharged. Few people live along the Botswanan border and little drilling and groundwater exploration has been done. The southern part of the Stampriet Artesian Basin borders the South African Kalahari National Game Park and the Gordonia District. In Gordonia, the water quality of the Karoo aquifers appears to be as poor as in the Saltblock in Namibia.

The Auob and the Nossob aquifers are confined and free-flowing (artesian) in the Auob valley at and downstream of Stampriet and in the Nossob valley around Leonardville. Elsewhere sub-artesian conditions prevail, that is, the water in the aquifer is confined, but the pressure is not sufficient for the water to rise above the surface.

Hoachanas fountain with monument for the dog that found the water

Factors such as climatic variations and the construction of large storage dams in river networks upstream of the aquifers, which have the effect of cutting off large floods that would otherwise feed the Stampriet Artesian Basin system, make it difficult to quantify this resource.

The recharge mechanisms of the aquifers are better understood. A recent satellite image interpretation of the area, done for the purposes of the Hydrogeological Map by a BGR expert, detected "sinkholes" within the Kalahari. These are small, shallow depressions caused by dissolution of calcrete where local runoff is concentrated and fed into permeable layers or structures below. From here the water reaches the artesian aquifers below. Such sinkhole areas exist in the north-west, west and south-west of the basin.

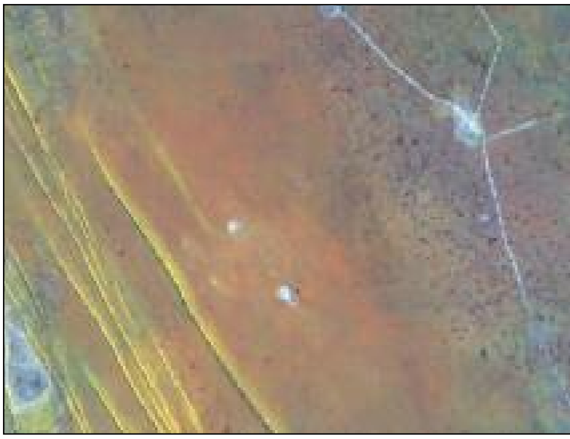
Wilhelm Struckmeier

Water level recorder near Stampriet high above ground measuring the artesian water level

First indications are that the artesian aquifers are recharged here during years with abnormally high rainfall. Within weeks after heavy rainfall events, the water level in boreholes sunk into the confining layers of the aquifer some 50 km from the recharge area, begins rising. The water in the artesian aquifers has almost no, or only a very weak isotopic evaporation signal. In contrast, a noticeable proportion of the rain that falls on the sandy Kalahari surface elsewhere, evaporates and the groundwater in the Kalahari layers of the central parts of the basin has a definite evaporation signal. These recharge investigations are continuing.

Utilisation of Groundwater

Presently water in the area is used for stock watering and increasingly for irrigation purposes. Although irrigation has economic advantages such as creating job opportunities, the groundwater resources are limited and need to be protected. The modelling results of the current development project indicate that the resource is over-utilised and a 30 % reduction in abstraction is necessary. Less wasteful irrigation methods, reduced evaporation from reservoirs and drinking troughs, and reduction of other losses will result in sufficient savings, in other words, water demand management needs to be implemented here.



Landsat Thematic Mapper

Satellite image showing small sinkholes in the calcrete

Most of the water supply schemes in the Stampriet Artesian Basin extract groundwater from the Auob aquifer, only Koës uses the Nossob aquifer. The subartesian boreholes at Aminuis (3) have maintained high yields since installation, but boreholes on the same aquifer at Onderombapa school (75) north of Aminuis and Kriess school (51) on the Weissrand east of Gibeon, have comparatively low yields. Over-abstraction causes large drawdowns in the low to moderate-yielding boreholes of the Leonardville (54) water scheme. At Aranos (7) supply problems are experienced from time to time even though the aquifer can provide sufficient

Jürgen Kirchner

Irrigation from groundwater produces green from oases in the Stampriet Artesian Basin water of a good quality. Very fine sand enters through the borehole screens at higher pumping rates and leads to operational problems and silting up of boreholes.

The Auob aquifer at Gochas (34) is overlain by approximately 150 m of Kalahari sediments, which contain poor quality water. Boreholes in town were contaminated with Kalahari water and a wellfield was established 10 km to the north on the farm Urikuribis, where water of Group A quality is found. The Auob aquifer is artesian at Stampriet (95), a village founded by missionaries who used the free-flowing groundwater for garden irrigation. At Koës (48), a village north-east of Keetmanshoop near the edge of the Saltblock, the subartesian boreholes draw water from the Nossob sandstone. J KIRCHNER

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Fish River - Aroab Basin

Much of the area east of the Namib sand sea between Mariental in the north and Ariamsvlei in the south is underlain by sedimentary rocks of the Nama Group and thus forms the large hydrogeological unit of the Fish River Basin and the Keetmanshoop - Aroab area.

The largest town and regional centre, Keetmanshoop, has a surface water scheme fed from Naute Dam. Smaller towns like Aroab, Maltahöhe, Kalkrand, Gibeon, Berseba and Bethanien rely on groundwater extracted from aquifers in Nama sediments. The landscape is extremely barren and rocky with little soil cover. The vegetation consists of dwarf shrubs with some trees in riverbeds. The main economic activities in the area are small stock farming and tourism.

Geology and geomorphology

Due to their predominantly horizontal bedding, rocks of the Nama Group tend to weather and erode in layers, resulting in flat plains, with major drainages forming canyons and gorges. Erosion produces rock fragments or clay-size particles and rivers accumulate very little sandy alluvium. The western boundary of the Nama Group is clearly defined as the major escarpment adjacent to the Schwarzrand, while to the east, the escarpment of the Weissrand, made up by younger deposits of the Stampriet basin, forms the natural boundary.

The Nama Group is subdivided as follows:

Group	Sub-group	Formation	Lithology
Nama	Fish River	Gross Aub	Red shale and red sandstone, locally greenish.
		Nababis	Red shale and red to purple sandstone, locally greenish.
		Breckhorn	Red to purple quartzitic sandstone and some subordinate red shale.
		Stockdale	Basal red to purple coarse grained quartzitic sandstone with thin conglomerate layer. Red friable sandstone, shale.
	Schwarzrand	Vergesig	Green shale with green and red sandstone.
		Nomtsas	Reddish shale and reddish sandstone, becoming green south of Maltahöhe, with basal coarse conglomerate in many places, limestone towards the south-west.
		Urusis	Greenish shale and greenish sandstone (in the north), with dark blue limestone and black limestone inter-layered and intercalated (in the south).
		Nudaus	Green shale and greenish sandstone, grey to greenish quartzite.
	Kuibis	Zaris	Bluish-green shale, sandstone, pink and grey to black limestone.
		Dabis	Grey to white quartzite, some grey dolomitic limestone, grey to greenish quartzite.

The lower part of the Nama Group was deposited in a shallow to moderately deep sea, divided into two embayments by the easterly trending Osis ridge, resulting in a facies differentiation between north and south in the Kuibis Subgroup. With increased thickness of sedimentation, the upper part of the Schwarzrand Subgroup and the overlying Fish River Subgroup were little affected by facies changes. The sedimentation of the Kuibis Subgroup took place in the late Cambrian Era, and all the rocks of the Nama are older than 450 million years (Ma). All units of the lower Nama Group thin eastwards and many pinch out, e.g. the Kuibis Subgroup is reduced to the Kanies Quartzite Member east of the Karas Mountains.

Major tectonic uplift affected the Nama at the end of the Schwarzrand deposition. Dips, in general, are very shallow to the east, except where folding has taken place and in areas where doming has resulted in locally shallow dips, radially away from the dome, e. g. in the Ubiams-Vleiveld area. The Nama Group rocks rest unconformably on older basement. Over most of the outcrop area the Nama is not folded, however, intensely folded Nama sediments are found between Gobabis and the Sossusvlei area. Faults generally, but not always, strike in a northerly direction and have been mapped quite frequently across the entire outcrop area. Extensive swarms of joints appear throughout the Fish River Subgroup.

Hydrogeology

Rock types of the Nama Group are inherently impermeable with little or no primary porosity. Groundwater is hosted in secondary features like faults and joints in sedimentary rocks of clastic origin (sandstone, quartzite and shale) and in solution features in limestones and dolomites. In the Hardap and Karas regions water levels are generally shallow in the east, close to the course of the Fish River, but become progressively deeper towards the escarpment in the west, where water levels deeper than 200 m are recorded. Drilling targets are mostly tectonic features such as faults and joints.

Frank Bockmühl

Drill site selected on a north-striking, west-dipping fault in Nababis Formation sandstone

These targets can be located by geological surveys, especially with the help of aerial photography. Detailed fieldwork is essential in locating and identifying the dip of faults and to appropriately determine the optimal site for drilling. (On the photo the dip of the fault can be clearly recognised from up-turned fractured sandstone, especially in the top right hand corner.) Faults can be risky drilling targets. Collapse at several depths requires that boreholes be drilled at various diameters to install successively smaller diameters of casing ("telescoping").

Frank Bockmühl

North-striking east-dipping fault, sandstone, Nababis Formation. Farm Aneis, along District road No 1075

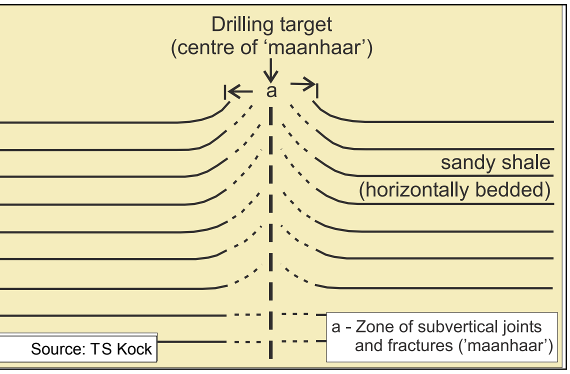
Jointing in the Fish River Subgroup is quite often only recognised during a field survey. These structures are mostly vertical to sub-vertical, and once identified, drilling sites can be placed quite accurately. Joints are often discernible by a linear "anticlinal" feature. A narrow band of upturned shale and/or sandstone within otherwise horizontally bedded layers is probably a result of swelling of the more argillaceous horizons due to percolation of groundwater and infiltration of rainwater along the strike of the joint.

The various formations of the Fish River Subgroup have different hydrogeological properties. In the younger Gross Aub Formation water tables are shallow and drilling targets can be selected geologically with good success. A high success

Frank Bockmühl

Drillsite placed on a joint in the Breckhorn Formation, intercalated sandstone and shale

rate can be achieved in the Nababis Formation with careful selection of drilling sites. Water levels are generally deeper than in the Gross Aub Formation. In the older Breckhorn and Stockdale formations, up to 30 % of the recorded boreholes were dry, due to the deeper water table and resultant difficulty in accurately determining a drilling site. With more precise fieldwork, the probability of intersecting groundwater on suitable structures should increase. In the Schwarzrand and the Kuibis subgroups, drilling sites should be selected on tectonic structures or contacts between limestones and clastic rocks. The water quality in the Fish River Group is in general acceptable, even though high nitrate concentrations can occur. Increased nitrate concentrations are almost always a result of contamination due to human and livestock activities close to the boreholes. This type of pollution is irreversible, but new boreholes can be protected by keeping people, their sewerage systems and livestock pens further away.



Source: TS Kock

"Maanhaar" features may indicate good drill sites

Groundwater use

The production boreholes at Ariamsvlei (8), a border post between Namibia and South Africa, were drilled into fractured sandstone and shale of the Schwarzrand Subgroup. These rocks are weak aquifers that receive only limited recharge due to the low rainfall in this area. The water is very hard and of Group B-C quality.

Amas is a farm 20 km north-east of Karasburg (43), on which a prominent fault in quartzitic sandstone of the Kuibis Subgroup along the Ham River gives rise to a strong permanent fountain. The river provides regular recharge to the fault zone. In 1985, boreholes were drilled to determine whether the aquifer had sufficient groundwater to augment the supply to Karasburg. A long-term pumping test conducted in 1993 indicated a production potential of up to 100 000 m^3/a.

The effect of tectonics on the yield potential becomes clear when the schemes at Berseba (14) and Gainachas (29) are compared. Both are situated at the foot of the extinct Brukkaros crater and underlain by shale and sandstone of the Fish River Subgroup. The Brukkaros extrusion has fractured the Nama sediments at Berseba and created major water bearing zones. The production boreholes draw from an extensive aquifer and provide much more water than the scheme at Gainachas where the absence of large fracture zones results in very low yields.

The same principle applies to the Kuibis and Schwarzrand Subgroups. The domestic water supply for Bethanien (15) comes from a fracture in sandstone, limestone and shale of the above subgroups, cutting across the Konkiep River north of the town. Bethanien must be the only town in Namibia to complain about an excess of groundwater. In the past, many inhabitants used private boreholes to water their gardens and the soil became waterlogged. Yet, the Kosis school (50) situated south-east of Bethanien obtains insufficient water from the slightly fractured sandstone and shale of the Schwarzrand Subgroup.

Even though Gibeon (30) lies on the Fish River, there is no groundwater of suitable quality to supply the town. Boreholes in town were used in the past, but had very high salt concentrations (TDS 2 000 - 8 000 mg/L). The closest, suitable, supply source of sufficient volume and quality was found on the farm Orab 40 km north of Gibeon. Very high-

Aroab water supply scheme (9)

The village of Aroab is situated some 165 km east of Keetmanshoop in an area underlain by sandstone with subordinate shale layers of the Nababis Formation, Fish River Subgroup.

These rocks are covered by calcrete of the Kalahari Sequence north of the village and Quaternary sand dunes in the east. Boreholes in the sand-covered area east of the village have high nitrate concentrations, because rainwater washes animal waste into the pans, the nitrates dissolve and infiltrate into the groundwater. Boreholes in the area where the Nababis Formation is not covered are all of good quality.

The old existing production boreholes were located close to the village of Aroab on the watershed. These boreholes had a history of declining yields and nitrate contamination. During 1986 new boreholes with better water quality were drilled south of Aroab. Drill sites were selected on joints and on the Kannenberg fault, a prominent west-striking feature on the farms Kannenberg, Koertzebeb and Nobees, after a detailed hydrogeological investigation. The groundwater gradient in the area is from north to south. Groundwater thus drains away from Aroab and accumulates in the Kannenberg fault, which acts as a conduit. With increasing distance from the existing pumping scheme, yields of the new boreholes increased drastically from 5 to 50 m^3/h. The results of the 1986 work clearly indicate the value of detailed hydrogeological investigations, preceding all major drilling exercises.

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yielding boreholes were drilled on a fracture crossing the Fish River that extends northwards as part of a fracture system underneath Hardap Dam. There is thus always abundant recharge from surface water. Similar to Gibeon, Maltahöhe (55) obtained groundwater from boreholes in the Hutup River in the past. When these became insufficient, a new wellfield was established in a tributary north of the town. The area around Maltahöhe is characterised by shale and sandstone of the Stockdale Formation, which belongs to the Fish River Subgroup. The groundwater potential of these rocks is generally low, but high yields are obtained on extended fracture zones like the one at Maltahöhe.

Kalkrand (41) lies halfway between Rehoboth and Mariental on a plateau of Karoo basalt (Kalkrand Formation). The basalt itself contains groundwater of poor quality and Kalkrand's water supply is obtained from boreholes on the farm Gurus approximately 20 km to the south, where the basalt is underlain by sandstone and shale of the Fish River Subgroup. High-yielding boreholes were drilled on a fracture system that crosses the Fish River and receives regular recharge. The water scheme at Schlip (91), a rural centre west of Kalkrand, with a fast growing water demand, draws groundwater from fractured Nama Group sediments.

The original boreholes were drilled on limestone and shale of the Kuibis Subgroup, while a new wellfield was located on quartzite and sandstone of the Schwarzrand Subgroup. The upper aquifer is unconfined, but the lower Schwarzrand aquifer is confined by a shale layer. The yields are moderate to high (5-35 m^3/h), and the water quality is Group A-B.

Tses (98) is a mission station between Mariental and Keetmanshoop that has grown into a fairly large settlement despite limited water resources. The geology consists of Dwyka shale (Nama Group), which is generally a weak aquifer. Boreholes of moderate yield were drilled on fractures crossing rivercourses. Several new boreholes have recently been added to the scheme. The water quality has deteriorated due to over-abstraction and lack of recharge.

F BOCKMÜHL

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Southern Namib and Naukluft

The Namib sand sea and Sperrgebiet, formerly known as Diamond Areas 1 and 2, extend along the southern coast of Namibia. Bordered by the natural boundaries of the Kuiseb River, Atlantic Ocean and Orange River to the north, west and south, the eastern boundary was drawn parallel to the coast 100 km inland. The Namib sand sea between the Kuiseb River and the Aus-Lüderitz road forms part of the Namib-Naukluft Park, except for a small coastal strip between Lüderitz and Gibraltar Rock, which is part of the Sperrgebiet. The Naukluft Mountain massif in the north-east has been included in this chapter because most of the drainage is directed towards the Namib sand sea. The area between Lüderitz and Oranjemund is still dedicated to diamond mining and closed to the public.

Oranjemund and Lüderitz, both at the coast, are the only towns in the area. The tourist camp at Sesriem and the village of Aus are situated on the eastern boundary. The Namib sand sea is an extremely arid zone with erratic rainfall in the summer season, while the Sperrgebiet receives sporadic winter rainfall. The only permanent water in this region is the Orange River, which supplies water to towns and mines (Oranjemund, Rosh Pinah) as well as agricultural and tourism projects.

Small stock farming is practised on farms east of the desert, but most of the development in the area is derived from mining. Diamonds are the target of the NAMDEB mines on the coast and on the banks of the Orange River. Diamonds are dredged in several offshore concession areas. A lead-zinc deposit is mined at Rosh Pinah, and a new zinc mine is being developed at Skorpion close to Rosh Pinah.

Geology and geomorphology

The Naukluft Mountain area dominantly consists of fractured and karstified dolomites and limestones of the Damara Sequence representing a so-called nappe complex. The nappes, tectonically rather complex features, have been overthrown on the older, low permeable Schwarzrand and Schwarzkalk layers of the Nama Sequence.

The Namib sand sea displays most of the dune types that can be found in the world, ranging from simple barchan through compound transverse and complex linear to huge star dune forms. The dunes are interspersed with inselbergs and low mountain ranges. The older dunes are reddish and semi-stabilised, while the younger mobile dunes are light coloured.

The Sperrgebiet lacks extensive dune areas and is dominated by mountains, inselbergs, gravel plains, ephemeral watercourses and bedrock-floored valleys shaped by a harsh wind regime. Fossil soils from ancient land surfaces are preserved as silcrete and calcrete caps on hills and plains. Soils are poorly developed in the Sperrgebiet, gypsum profiles on stable gravel plains being the most common type.

While the geology of the Namib sand sea is hidden under a shroud of sand dunes and only glimpsed in isolated outcrops, the Sperrgebiet provides good exposures of the geological record dating back some 1 500 million years (Ma). The oldest rocks in the area are gneisses of the Namaqualand Metamorphic Complex that can be found in the Lüderitz area and along the eastern boundary, e.g. at Aus. The next period of rock formation occurred some 900 to 500 Ma ago and resulted in sedimentary and associated volcanic rocks, known as the Gariep Group. The Gariep Group corresponds to the Damara Sequence in the Khomas Hochland. Base metal mineralisation occurs in Gariep rocks at Rosh Pinah. In contrast, the Nama Group rocks in the Sperrgebiet are relatively undeformed limestones that accumulated some 550 - 500 Million years ago in a shallow marine basin.

Following the deposition of the Gariep and Nama groups, there was a considerable time break of some 350 - 400 million years. There is no record of the Karoo Sequence in the Sperrgebiet. The break up of the old continent comprising South America and Africa about 130 Ma ago gave rise to several volcanic complexes in the central Sperrgebiet. As the South Atlantic Ocean opened, extensive erosion formed the Great Escarpment and filled the offshore Orange Basin with more than 4 km of sediments during much of the Cretaceous period (120 - 65 Ma).

Towards the end of the Cretaceous, continental erosion waned and remnants of land surfaces were preserved as

Wynand du Plessis

Sossusvlei, where the Tsauchab River disappears

silcrete-capped hills. During the Tertiary, which lasted from 65 - 2 Ma ago, the climate became gradually more arid. The geological record of this period includes fluvial and sheetwash deposits (gravel, sand and clay), windblown sand (fossil dunes) and calcretes. The earliest Tertiary sediments are the Blaubock gravels in the central Sperrgebiet. The rivers depositing these gravels carried large trees from a nearby hinterland that today is devoid of such vegetation. Green and red fossil-bearing continental sediments are found in a number of valleys and depressions, e.g. in the Koichab River area. These sediments were laid down in shallow streams and floodplains whose catchments appear to have fallen mostly within the Sperrgebiet.

During the following drier phase, reddish sand dunes of the Tsondab Sandstone Formation were deposited. These slightly consolidated sandstones are found from south of the Kuiseb River to the Orange River. In the central Sperrgebiet, coarse gravel conglomerates overlie the red sandstones, indicating a change to wetter conditions. Rainfall within the Sperrgebiet probably increased to several hundred millimetres per year, generating runoff that transported gravels from mountains and inselbergs without incising deeply into the underlying sandstones. The Gemsboktal and Arrisdrift gravels of the Sperrgebiet correspond to the Karpfenkliff gravels in the Kuiseb valley.

During the following semi-arid phase, erosion diminished and calcareous soils formed on stable surfaces. These soils are today exposed as extensive calcrete surfaces that cover most of the plains and valleys of the Namib and Sperrgebiet. In the late Tertiary, drier conditions were probably instigated by the full development of the Benguela cold water upwelling system between 10 - 7 Ma ago. The accumulation of wind-blown deposits of the Sossus Sand Formation forming the Namib sand sea began during this time. The Sperrgebiet is a link between major components of a massive and long-lived sediment transport system. This system transports eroded material from the interior of southern Africa into the Atlantic Ocean, up along the West Coast, and back into the Namib Desert. Diamonds were carried along with other sediments and concentrated in one of the richest sedimentary deposits in the world.

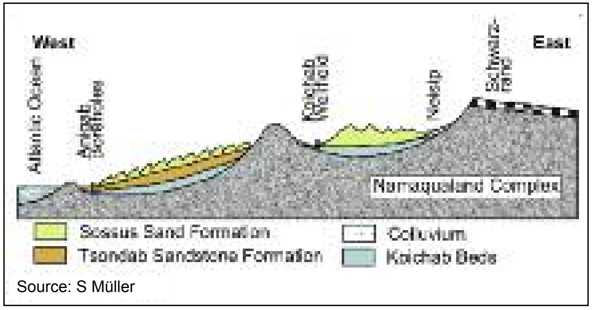
The arid climate of the Namib has, over the last several million years, been interrupted by short-lived wetter intervals. Wet periods occurred in the Namib during the Ice Ages of the Pleistocene. During these phases, rainfall was sufficient to sustain shallow pans long enough to precipitate lime, in some places as travertine. These were used by Stone Age people, as shown by the artefacts they left behind.

Hydrogeology

The carbonate rocks of the Naukluft are heavily karstified. Numerous springs and waterfalls are fed by this huge karst groundwater body which may be described as a natural lysimeter discharging above the low permeable sediments of the Nama Sequence. Also tufa or travertine formations are typical for the Naukluft. Although some drilling was done in the beginning of the last century, very little is known about the quantity, quality, and utilisation of the groundwater of the Naukluft.

Limited water availability in the Namib Desert presents the single largest constraint on development. Mean rainfall is less than 100 mm per year, meaning that sufficient rain to recharge the aquifers only falls in some years.

The occurrence of exploitable groundwater resources in the Namib Desert is closely linked to the existence of alluvial aquifers created by perennial, ephemeral or even fossil rivers. The only abundant source of groundwater in the Sperrgebiet is the alluvial aquifer along the Orange River, which provides a secure supply to Oranjemund. The ephemeral Kuiseb River along the northern boundary of the



Source: S Müller

Cross-section in the southern Namib from the Schwarzrand to the Atlantic Ocean

Namib sand sea supplies groundwater to Walvis Bay as described earlier in this chapter.

The westward-flowing endoreic rivers that terminate against the Namib sand sea today flowed into the Atlantic Ocean during phases of wetter climate in the past. Examples of these are the Tsondab, Tsauchab and Koichab rivers. Sediments laid down by these rivers are found underneath the dunes in former riverbeds, called paleo-channels. Under present conditions, surface water infiltrates in the upper reaches and flows as groundwater in the paleo-channels, discharging into the ocean. Some of this groundwater emerges in small freshwater springs along the coast. The more prominent ones are at Sandwich Harbour (paleo-channel of the Kuiseb River), Meob (Tsauchab River paleo-channel) and Anigab north of Lüderitz (Koichab River paleo-channel).

Tsondab and Tsauchab Rivers: The alluvium of the Tsondab and Tsauchab at the foot of the escarpment shows a moderate yield, which is quite remarkable in this arid area. Both rivers provide water to tourist establishments. At Sesriem, the Tsauchab River is deeply incised into a thick calcrete layer and water can be found almost permanently in a spring at the head of the canyon.

Koichab River: The water supply to Lüderitz is based on fossil water reserves in the Koichab paleo-channel. The Koichab wellfield (49) is situated 100 km north-east of Lüderitz at the foot of a massive dune formation up to 200 m high. The Koichab area was proposed as early as 1914 as the most suitable source of water supply for the growing town of Lüderitz, however a water supply scheme was only established in 1968.

A section of the area shows the recent dunes of the Namib sand sea underlain by fossil dunes of the Tsondab Sandstone Formation, neither of which contains groundwater. Under the Tsondab, or directly under the recent dunes, are Tertiary sheetwash deposits, locally referred to as Koichab beds that consist of a mixture of clay sand and gravel. Occasional layers of clean sand and gravel are good aquifers with yields of 5-50 m^3/h, while the predominant clay and silt layers are aquitards.

The Koichab wellfield covers an area of 20 x 3 km^2 with an average aquifer thickness of 50 m and water level at 16 m. Radiocarbon analyses show that the groundwater in the Koichab River aquifer is fossil water some 5 000 - 7 000 years old. It is of Group A quality and one of the best waters found in Namibia. Monitoring of the water levels indicates that no direct recharge reaches the wellfield due to the low average rainfall of 80 mm/a and the presence of clay layers covering the aquifer. There might be recharge in the upper reaches of the Koichab valley originating from the Neisip River. Recharge to the Neisip area of 2 Mm^3/a was estimated, but isotope analyses indicate a flow velocity to the wellfield of only 13 m/a. The slow decline of the water table in the wellfield shows that depletion of the resources occurs, despite infrequent recharge. It is estimated that the stored reserves in the investigated part of the Koichab paleo-channel are 1 600 Mm^3.

The Koichab paleo-channel discharges small volumes of freshwater in seepages at Anigab on the coast north of Lüderitz. This aquifer was investigated in the 1960s as an alternative water source for the town, but the quantity and quality were insufficient.

Dieter Plöthner

Well in the Koichab Pan

Emergency grazing in the Sperrgebiet

From the 1950s to the early 1980s, areas of grassland in the eastern Sperrgebiet and the Koichab area north of Aus were used for emergency grazing.

Evidently the Kaukausib Fountain and waterholes in the Koichab River were used for watering livestock until the late 1950s. This was apparently not for emergency grazing but as a watering stop for livestock driven from the interior to Lüderitz or Oranjemund for slaughter.

Sperrgebiet, waterhole near Koakasib

In 1951, drought-stricken farmers in southern Namibia requested that all the land of pastoral value inside the Sperrgebiet be made available to graze their livestock. In response, boreholes were drilled and a 16 km-wide strip of land running along the eastern fence was allocated for grazing. Drilling records of these boreholes show the limited potential of the aquifers. Many boreholes were dry or had very low yields just sufficient for stock watering. Between 30 000 and 60 000 sheep were kept in the area, which was subsequently widened by 8 km in 1955.

Emergency grazing was again permitted in the mid-1960s and during the severe drought of 1981-82. It was stipulated that grazing was to be made available only to those farmers whose own grazing was completely depleted and who did not have access to other fodder.

Groundwater resources in fractured bedrock aquifers of the Namib and the Sperrgebiet are very limited and, if exploited, extraction easily exceeds recharge. The town of Aus situated among hills of Namaqualand granite-gneiss on the border of the Namib Desert is an example of a town whose development is restricted by insufficient water resources (10). The average annual rainfall of below 100 mm provides little groundwater recharge. Local aquifers of limited extent are found in fracture zones, but the borehole yields are low (1-5 m^3/h). Dozens of mostly dry boreholes were drilled in and around the town to augment the water supply, until it became clear that no significant new resources could be found in the vicinity.

Very few aquifers are found in the western part of the Sperrgebiet. In the early 1900s, boreholes were drilled in Gariep dolomite at Grillenthal to supply the mine at Elisabeth Bay, but other diamond mines had to bring their water in barrels from Lüderitz. The number of boreholes and kilometres of pipeline required to support even short-term emergency grazing in the eastern part of the Namib are testimony to the scarcity of groundwater in this area.

S MÜLLER

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Karas Basement

The greater portion of the area is an erosion plain sloping south towards the Orange River where it becomes highly dissected. In the east, and to a lesser degree in the north, an escarpment formed by overlying Nama sediments defines the borders of the area under discussion.

The western and south-western areas are mountainous. Drainage is normally dendritic from the north towards the Orange River. The dominant ephemeral river is the Fish River with its deep canyon in the Ai-Ais Nature Reserve. Smaller rivers are the Kainab, Ham and Udabis in the east, and the Velloor and Hom rivers in the central portion. The Haib, Aniegamoep and Gamkab rivers expose basement towards the west.

Karasburg is the only town in the area, while small villages exist at Grünau and Warmbad. The Karas Region is an arid zone with low and erratic rainfall of about 50-100 mm/a, which can occur in the summer and winter seasons. A sixty-seven year mean for Karasburg of 123 mm/a was calculated in 1990. The only permanent water is the Orange River, which is used for an agricultural project at Aussenkehr. The area is sparsely populated because farms must be extremely large to be economic. Most activities focus on small stock farming and tourism.

Geology

Basement outcrops in this groundwater basin are of Mokolian age (1200 to 2 000 Ma) and are divided into the Haib Group and Vioolsdrif Granite Suite Complex in the west and south-west, and the Namaqua Metamorphic Complex in the eastern and north-eastern areas. Intrusive rocks like granite, augengneiss, gabbro, norite and pegmatite are generally younger than the meta-sedimentary and meta-volcanic rocks. Widespread outcrops of Mokolian basement rocks occur from south of Karasburg to the Orange River. Warmbad is centrally situated in this area. Another basement outcrop is found from 20° E to south of Rosh Pinah along the Orange River. An area stretching generally north-east from the southern boundary of the Ai-Ais Nature Reserve through the Grünau-Holoogberg area towards the Karas mountains is also largely underlain by basement.

Frank Bockmühl

Old German fort at Warmbad

The basement rocks were exposed to erosion and weathering for up to 600 Ma, during which a paleo-landscape was formed. During the late Namibian (± 650 Ma) to Cambrian Period (± 500 Ma), the basement rocks were partially covered by sedimentary rocks of the Nama Group, which in turn were partially covered by Karoo-age sediments (Carboniferous to Permian 345 to 230 Ma). Post-Karoo dolerites of Jurassic age intruded into the Karoo sediments. The younger horizons were subsequently eroded re-exposing the basement. Erosion started in the south and presently has reached the area south of Karasburg, where deeply incised rivers like the Hom open windows of basement. The youngest unconsolidated sediments of Quaternary age are found south-east of Warmbad overlying rocks of the Namaqua Metamorphic Complex.

Major regional north-west striking faults have displaced the Haib Group and Vioolsdrif Granite Suite Complex against the Namaqua Metamorphic Complex. A second regional fault line strikes from the farm Hakiedoorn at the Orange River north-east in the direction of Warmbad to the farm Norechab. Abundant smaller faults have been mapped, indicating no preferential direction of strike.

Hydrogeology

Very limited volumes of groundwater are available in the basement rocks of the southern Karas Region, since there are no productive aquifers. Lack of recharge and poor groundwater quality in most areas further aggravates the situation.

The area has long been inhabited, as the abundance of old hand-dug wells indicates. Most wells are situated along rivercourses in shallow alluvium and deeply weathered channels and basins. Wells in the Warmbad area were mostly dug before 1930. Very few boreholes were drilled before 1920, and these also mostly close to rivercourses. Artesian boreholes were drilled on the farm Nieuwefontein Ost east of Karasburg. Natural fountains occur predominantly in riverbeds. At Warmbad, a thermal spring is fault controlled (±34° C), and at Tzamab-Gründorn, some 3 kilometres north of Hamab station another warm spring is associated with an inlier of gneiss. The most well known hot water spring is found at Ai-Ais, a popular tourist resort on the Fish River. The temperature of the spring water is 66.5° C. It emerges from a fracture zone in granite and gneiss.


Wilhelm Struckmeier

Ai-Ais hot spring eye

Exploration for groundwater should be concentrated along faults, and where possible close to riverbeds, in order to facilitate and enhance recharge. Weathered and decomposed zones within the granitic terrain close to riverbeds might be promising targets. Geological investigations and geophysical methods to determine drilling sites are essential in maximising success rates. Electromagnetic surveys as well as electrical resistivity sounding and profiling arrays have been successfully employed.

The only detailed survey of boreholes and wells in this area has been conducted by the CSIR in 1969. During this survey, water samples were collected from 338 boreholes, wells and artesian boreholes. There were 445 dry boreholes recorded, but it is presumed that only a part of these were found. Dry boreholes are significantly located mostly on, or close to, the watershed between the Hom and Ham rivers. The depth of boreholes was generally under 130 m, with the majority being shallower than 50 m. Water levels during the CSIR survey were mostly shallower than 30 m. Yields below 2.3 m^3/h were recorded for 63 % of the non-dry boreholes, while only 16 % had yields over 5.4 m^3/h.


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Drill site WW 33768 selected geologically to intersect a partly silicified, faulted contact (ridge in background) forming an east-south-east trending feature (Borehole drilled to 100 m depth, waterstrike at 61 m, blowtest yield 2.89 m^3/h, RWL 53.38 mbgl, Group B).

Nearly 80 % of all the water sources surveyed were unsuitable for human consumption, mainly due to high concentrations of fluoride and nitrate and to a lesser degree sulphate. Only 20 % of the water sources analysed proved unsuitable for livestock watering, in this case due to high sulphate contents.

The water supply situation at Grünau (35) and Warmbad


Frank Bockmühl

Fault controlled drainage channel enhancing recharge in decomposed granites

Gabi Schneider

Paleoproterozoic rocks at the Orange River

(103) is typical for areas underlain by granite-gneiss of the Namaqualand Complex. Groundwater around Grünau occurs in fracture zones recharged by small rivers and on contact zones of younger dolerite dykes. The groundwater potential is low and the available resources are far from sufficient to meet the demand. The groundwater flow direction is north-west to south-east. Water of Group B-C quality is found north-west of the village, but gradually increasing salinity and fluoride concentration make the groundwater non-potable at Grünau and further to the south-east.

Warmbad was established by missionaries and was the capital of the south until this role was taken over by Karasburg. The town is on the Hom River downstream of the Dreihuk Dam. The Namaqualand granite-gneiss along the riverbed is deeply fractured and contains highly mineralised water of Group C-D quality. The fluoride concentration is often too high for human consumption and water treatment was considered in the past.

F BOCKMÜHL

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Karasburg water supply and Dreihuk Dam

Karasburg (43) experienced recurrent water supply problems until the Dreihuk Dam was built to supply the town with surface water.

Until now the dam has never completely filled up, but at least helped by supplying some additional water from the seepage well as described below. Karasburg is situated on Dwyka shale and tillite of the Karoo Sequence, which are intruded by dolerite dykes. One such dyke forms the base of the dam wall of the Bondels Dam. It acts as an underground weir damming up groundwater in the fractured shale aquifer, on which the Bondels wellfield is located. High yields of 10-30 m^3/h are obtained from these boreholes, while older boreholes on less fractured rocks in town have very low yields. A potential additional wellfield for Karasburg was investigated on the farm Amas 20 km north-east of Karasburg. This area is underlain by Nama sediments and thus described in "Nama Basin".


DWA Archive

Dreihuk Dam

In 1977 the Dreihuk Dam was built across the deeply incised valley of the Hom River, 16 km south-west of Karasburg. The site was geologically evaluated and found unsuitable, because prior to the sedimentation of the Karoo shale, the palaeo-surface was exposed to weathering and the weathered surface was not eroded later, but is still present underneath the remaining cover of Karoo rocks. The deeply incised Hom River cuts through the Karoo and exposes the weathered zone, which can be several metres thick. When there is water in the dam the weathered zone becomes transmissive and water from the dam basin seeps through to the downstream side of the dam wall. A drainage pipe and sump (pit) in the eastern side of the dam wall were constructed to collect seepage and this water contributes significantly to Karasburg's supply, about 60 000 to 190 000 m^3/a depending on the water level in the dam. The pit can also be used for Gabis mission (28), which in the past relied entirely on two boreholes drilled into the weathered zone downstream of the dam.

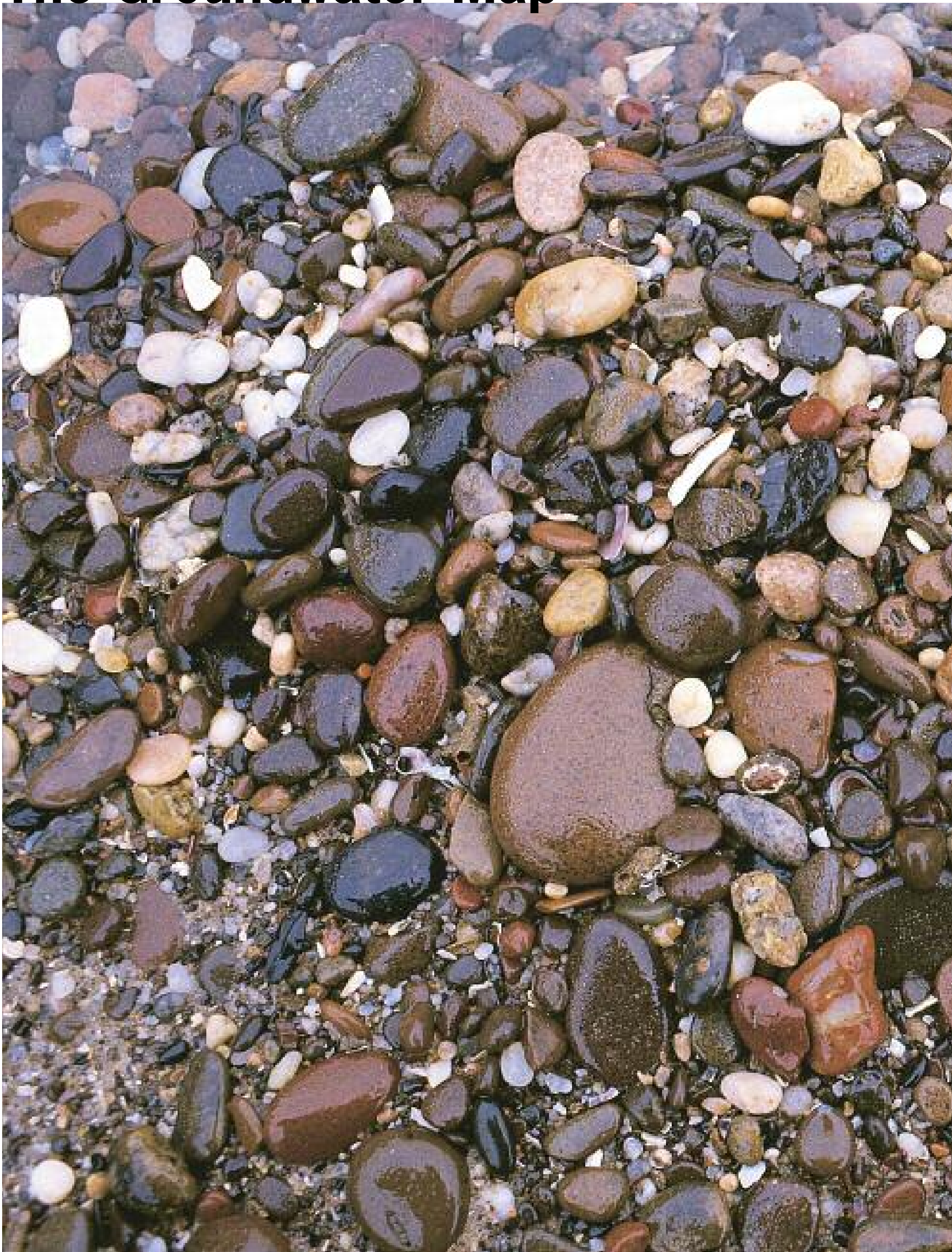

DWA Archive

Water seeping through the dam wall of the Dreihuk Dam

The water quality at Dreihuk is generally poor as long as there is no inflow into the dam. High concentrations of sulphate, chloride and sodium result in Group D water. After inflow, the water quality of the drainage pipe and pit temporarily deteriorates due to a flushing effect, but it improves some time later to Group B quality.

F BOCKMÜHL

The Groundwater Map



Wynand du Plessis

Data and use of the Map

This chapter describes the technical way in which the data used for the Map were collected, created, interpreted and finally prepared. A basic distinction is made between data serving as topographical background information, and the thematic data layers which were constructed, calculated or derived from various sources. The problems in the creation of the topographical base data were mainly due to incomplete, inaccurate or non-documented data sets. The creation of the thematic data themes, relied on the geological, hydrogeological and hydrological data of variable quality captured over the past decades and necessitated a huge effort to search, collect, correct and validate the data. Nevertheless, this process of preparing coherent and good quality data for the Hydrogeological Map has resulted in the most up to date, accurate and complete data sets on ground- and surface water in digital form yet in the MAWRD.

It must be clearly stated, that the data collected for the Hydrogeological Map of Namibia Project (HYMNAM) was first and foremost geared at establishing a national, country-wide map at a scale of 1:1 000 000, with 10 millimetres on the Map equal to 10 kilometres in reality. This focus on a country-wide overview map and the time frame of only two years has meant that the information on the Map is inadequate to allow zooming in and enlarging. More detailed, high-resolution data on geology, boreholes and groundwater might be available for certain regions of the country in the databases of GSN, DWA and NamWater, but cannot be derived from the HYMNAM data sets.

In addition, it must be spelled out clearly that site-specific projects such as the correct siting of boreholes or dump sites require sound, site-specific professional investigations. The information presented on the Map at 1:1 000 000 scale, is by far too general and can only be used as orientation for the site-specific follow-up studies. The results of the detailed investigations should be used to improve the HYMNAM data sets in the future.

Topographical base data

When the Hydrogeological Map of Namibia Project (HYMNAM) was initiated, it was assumed that the topographic base data for the Map were readily available in the country. In fact, it soon became apparent, that the accessibility of digital data of good quality and reliability was, and still is, one of the major challenges in Namibia. Another challenge faced throughout the data-capturing period was that existing data sets were of a poor quality or occurred in strange electronic formats lacking any documentation. This made it very difficult to collect the data and transform it into a consistent and correct coverage.

The first step was to implement a geographical reference system to be used throughout the Map project. Taking into account the reference systems for existing data, the following projection was chosen:

Type	Albers Equal Area
Units	Metres
Spheroid	Bessel 1841
1st standard parallel	-26 00 00
2nd standard parallel	-20 00 00
Central meridian	18 30 00
Latitude of origin	-22 00 00
False easting (metres)	0
False northing (metres)	0

As the HYMNAM Project and the Hydrogeological Map depended greatly on a reliable topographical database, the creation of this was considered the first important step to ensure that all new thematic data fit together geographically and logically. The data sets representing the topographical background displayed on the Map were collected or prepared as shown in the next table.

Numerous corrections were applied to the drainage pattern because it is both a topographic and a water-related feature. The most accurate and complete data set available was the Map created by the Ministry of Environment and Tourism (MET) based on the Digital Chart of the World, which is publicly available and compiled from various data sources. Error corrections and completions were necessary at certain places. For this, topographical maps at scale

Data sets representing the topographical background

Data Set	Source, Preparation
National border	Provided by the GSN; coast line and the rivers forming the northern and southern boundary were re-digitised based on the Topo sheets 1:250 000 as well as satellite images
Regional boundaries	Provided by the Roads Authority (S Thekie, J van Rensburg)
Nature conservation areas	Provided by MET (H Kolberg)
Towns	Provided by the Roads Authority (S Thekie, J van Rensburg)
Roads	Provided by the Roads Authority (S Thekie, U Truemper)
Railways	Provided by GSN
Powerlines	Provided by NamPower (U von Seydlitz)
Mines	Provided by GSN
Pipelines and canals	Provided by MET/NNEP and NamWater
Rivers	Basic data provided by MET; corrections applied by DWA based on Topo sheets 1:250 000 and satellite images
Oshanas, Swamps, Lakes/Reservoirs, Pans	DCW database; corrections applied by DWA based on Topo sheets 1:250 000 and satellite images
Catchment areas	Digitised from maps of DWA
Dams	Digitised on the base of information from NamWater
Springs	Digitised based on information from the national groundwater database; information gathered from existing maps, reports and field visits

1:250 000, drainage data sets of published and draft geological maps at scale 1:250 000, and finally, a set of LANDSAT Thematic Mapper satellite images were used to rectify and update the drainage pattern. The result is the most reliable data set on drainage in Namibia, applicable to the national scale of 1:1 000 000, yet errors may be still considerable, as high as 3 mm on the Map or 3 km in reality.

The second data set to receive attention was the country border. To show the total territory of Namibia in the correct topographic position, a new country border data set including the Caprivi Strip had to be developed. The country border was checked using existing maps at scale 1:250 000, a number of geodetic points along the border to Angola, Botswana and Zambia as well as the LANDSAT TM satellite images.

Few changes were necessary for the good-quality data sets such as the roads and towns that had been recently surveyed by the Roads Authority. For other data sets, no further information was available to improve the accuracy nor was it possible to rectify in the time available, nor within the budgetary constraints of the project.

Preparation of the thematic data layers

Landsat Thematic Mapper

In the Caprivi Strip, the old country border (red line) had to be substantially corrected (yellow line) using satellite imagery; the deviation exceeded 10 km

The thematic data layers displayed on the Map were compiled and derived using data from various sources, analogue as well as digital. In addition, the knowledge and expertise of experts working in the fields of groundwater and /or geology in Namibia were mobilised to extract the pertinent information from the existing data. The table below shows the thematic data layers together with the sources of information used for their construction:

The most important source of data, for the compila-

Data Set	Source
Lithology	Derived from the geological map 1:1000000, from satellite images, borehole completion reports as well as from knowledge of local consultants
Geological faults	Provided by GSN
Aquifer productivity	Derived from information in the national groundwater database of DWA, borehole completion reports and from knowledge of local consultants
Groundwater divides	Derived from information in the national groundwater database
Groundwater flow directions	Derived from information in the national groundwater database
Depth to groundwater table from surface	Derived from information in the national groundwater database and borehole completion reports
Surface water divides	Derived from the data layers of the rivers and the digital terrain model provided by the USGS (GTOPO30)
Areas of saline groundwater	Derived from information in the national groundwater database, the CSIR hydrochemical maps as well as from knowledge of local consultants
Areas with poor groundwater quality	Derived from information in the national groundwater database, the CSIR hydrochemical maps as well as from knowledge of local consultants
Areas of artesian and sub-artesian water	Digitised from documentation of DWA and knowledge of local consultants
Groundwater control areas	Digitised from maps of DWA
Groundwater irrigation schemes	Digitised based on information from the Division: Agricultural Engineering of the MAWRD
Groundwater supply schemes	Digitised based on information from NamWater

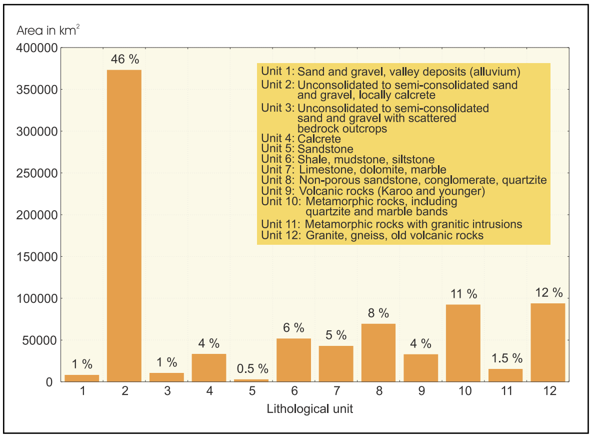
tion of the thematic data layers related to groundwater, was the groundwater database operated by DWA. The second main thematic layer displaying the lithological units is largely based on the existing geological map of the Geological Survey of Namibia at a scale of 1:1 000 000.

Lithology layer

The preparation of the thematic data set on the lithological layer took place in several steps. As a starting point, the units on the 1:1 000 000 Geological Map were arranged according to the rock types (lithology), because the type of rock determines the groundwater flow in it. Being of minor importance, the age and stratigraphical position were not taken into consideration. A legend describing the different rock types was created. This differentiation was gradually refined and finalised, using detailed documentation and the expertise of local geologists. Finally, the 164 units outlined on the geological map were reduced to the 12 units contained in the lithological data layer.

The area covered by each of these large lithological units is shown in the bar graph. Almost half of the country (48 %) is covered by unconsolidated deposits such as gravel, sand and silt, while 24 % are sedimentary hard rocks (limestone, dolomite, sandstone, mudstone, shale), 12 % metamorphosed sedimentary rocks, 4 % young volcanic rocks, and 12 % basement rocks, bringing the percentage of hard rock areas in which groundwater exploration is difficult, to 52 %.

Aquifer productivity

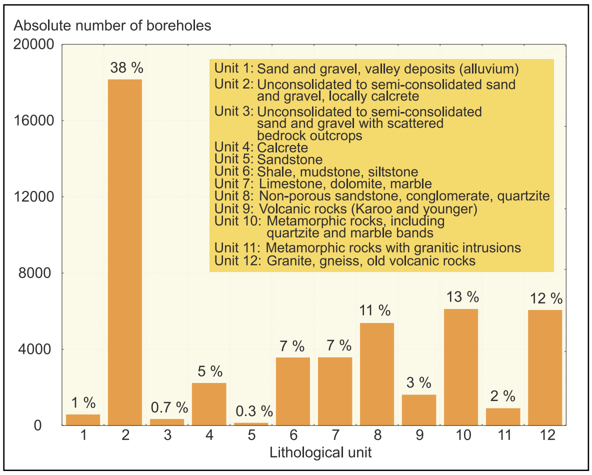


Area covered by the lithology units used on the Map

The current groundwater database stores information on positions, construction details, depth to water level and yields from about 48 000 boreholes. Problems encountered included missing values and wrong entries, due to the historical development of the database. It started as an application in a UNIX environment, was converted into a dBase file and finally into a MS-ACCESS database. This caused many errors due to lost tables, mixed up data sets and destroyed relationships between various tables. Now, DWA together with NamWater is developing a new database application (GROWAS) which will be ready by the end of 2001.

Nevertheless, the content of the database proved very useful and the influence of errors was minimised by the large volume of information available and the small scale of the Map, scale 1:1 000 000. The number of boreholes, and thus the reliability of information is shown on the inset map "Density of borehole information" on the main Map. This is reflected here in the graph showing the number of boreholes recorded in the database, per lithological unit of the Map.

The two graphs clearly indicate the correlation between the size of the area covered by the various lithological units and the number of boreholes drilled. Surprisingly, no unit stands out as a prominent aquifer with a high number of boreholes. Instead, the distribution of population and the demand for groundwater are decisive criteria for the number



Boreholes drilled in the lithological units

of boreholes in various parts of the country. Therefore, it is necessary to analyse the distribution of borehole yields to be able to delineate aquifers, aquitards and aquicludes.

The wealth of borehole completion reports was used to confirm and amend the information extracted from the database. These hardcopy documents are filled once a borehole is drilled. There are about 21 000 borehole completion reports in the files of DWA and NamWater. These reports comprise information about the borehole design, the initial yield during pumping tests and the lithological units encountered. In the compilation of the Map, only reports providing solid and complete information were used. A limited number of representative boreholes with a detailed lithological description and complete data sets on depth, yield and groundwater quality, were selected as reference boreholes and are displayed on the Map (see Annex 4 “Comparison of selected guideline values for drinking water quality”).

Reports from previous groundwater projects available in NamWater and DWA were scrutinised and checked to obtain complete and consistent data. Useful ones were selected and the information regarding groundwater potential, quality and use, as well as other important hydrogeological details were extracted for the Map. This information was used to confirm or adjust the information derived from the database and the completion reports.

Using this information, the second important layer, the aquifer productivity data set, was created step by step. Firstly, the yield figures stored in the groundwater database were analysed and spatially interpolated. The following categories were chosen, after discussion with local experts:

Yield in m^3/h	Human activities possible
< 0.5	Only emergency water supply or very small livestock
0.5 – 3	Small settlements with small stock units
3 – 15	Farming/settlements with a certain amount of large stock units
> 15	Farming/settlements with large stock units, municipal water supplies and irrigation

These yield figures and the aquifer type derived from a generalisation of the lithological layer, whether porous, unconsolidated deposits or fractured hard rocks, made it possible to map the country according to the International Legend for Hydrogeological Maps, recommended by the International Association of Hydrogeologists (IAH) and UNESCO (Struckmeier & Margat 1995). This legend uses a colour scheme that subdivides the rock bodies into aquifers and non-aquifers (aquitards and aquicludes). The latter are shown in two shades of brown, while the aquifers are further split into porous or fractured. This distinction is useful, because they have fundamentally different flow characteristics and thus groundwater investigation and exploitation also differs. Porous aquifers are shown in blue and fractured aquifers in green. Two shades of these colours are used to reflect the productivity. Dark blue and dark green represent aquifers with high potential (yields generally above 15 m^3/h), while light blue or green indicate aquifers with moderate potential (yields generally between 3 and 15 m^3/h).

The results of this data analysis exercise were discussed with the local groundwater consultants. They provided input based on their experience and specialist knowledge of certain areas of the country. Their input was all the more valuable, because few records exist about unsuccessful boreholes and thus the aquifer potential concluded from the database and other records was seriously overestimated in some areas. This could be corrected by those with local experience.

The other groundwater related data sets were established in much the same way. Firstly, the data available in the database were analysed and the results printed on the Map. Then, local groundwater consultants were solicited to rectify and adjust those results. This multiple-step exercise, combining information of different sources, evaluating it, discussing it and refining it, finally created the best picture of the hydrogeological situation in the country. Involving local hydrogeologists in this project also guaranteed that the experience and intuitive expert knowledge of individuals, not captured in any database nor documented, was harnessed for the Map.

Inset maps

There are five inset maps and three geological cross sections on the Map. These provide complementary information that, to retain clarity and legibility, could not be presented on the main Map.

In the inset map “Rainfall and main catchments in Southern Africa", at a scale of 1:10 000 000, the major rivers and their catchment basins are shown together with the rainfall distribution in southern Africa, south of 12° latitude. It clearly demonstrates that Namibia shares most of the surface water catchments with neighbouring countries and lies in an area of very low rainfall. The data for this inset map originated from the data set of the "SADC Water Resource Database" and from Arnestrand & Hansen, 1993; published in Pallett 1997, amended and revised on the basis of up to date Namibian sources.

The insert map "Altitude of ground surface", at a scale of 1:6 000 000, shows altitude intervals in metres above mean sea level. These contour lines were interpolated from the digital terrain model GTOPO30 provided by the US Geological Survey. This terrain model was developed using several data sources. The lateral grid size is about 900 m. The accuracy of the height information depends heavily on the data source used for a specific area and can be as low as ±80 m. Obvious errors in the data set have been corrected on the basis of topographic maps at scale 1:250 000.

The inset map "Groundwater quality", at a scale of 1:6 000 000, shows the TDS (total dissolved solids) values in boreholes throughout the country. The classification is according to the Namibian Guidelines (Annex 4), which classifies water according to quality criteria as Groups A (excellent quality water), B (good quality water), C (low risk water) and D (high risk water, unsuitable for human consumption).

The insert map "Density of borehole information", at a scale of 1:6 000 000, was created by calculating the numbers of boreholes existing in the database per topographical map sheet at 1:50 000. The information shown on this map together with the figures provide a good indication about the reliability of information, i.e. where in the country enough knowledge about the hydrogeological situation is available, and where information is lacking.

The inset map "Vulnerability of groundwater resources", at 1:6 000 000 scale, outlines the vulnerability of groundwater resources to pollution. The risk of groundwater pollution from the surface mainly depends on the depth to the water table, the type of the underlying aquifer (porous or fractured), the flow in the aquifers, and the amount of rainfall in the recharge area. The vulnerability map therefore integrates depth to groundwater, aquifer type, predominant flow and recharge from rainfall, takes these variables into account in a simple rating system, and shows where proper protection of aquifers from pollution is essential.

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The Map includes three cross-sections of important multi-layered aquifer systems in the country. The upper two intersect the Stampriet Artesian Basin and the bottom one intersects the karstified Otavi Mountain Land area and the adjacent areas to the north-west and south-east. These cross-sections emphasise the vertical dimension and highlight the fact that groundwater flow systems are 3-dimensional in reality. This is difficult to portray in the 2-dimensions available for a map. Sound interpretation of a hydrogeological map requires a constant awareness of the third dimension.

Use of the Map

The purpose of the Map is to provide the public as well as decision makers in the government and the private sector, with accurate information on the occurrence, utilisation and vulnerability of groundwater resources in the country. Ideally, it must provide answers to questions asking "where", "what" and "how much". Due to the small scale of 1:1 000 000 of the Map, it provides an overview for planning of new groundwater-related projects. For instance, it can assist in rough planning of environmentally sound new settlements, industrial sites, and water abstraction schemes. It can also be used as a strategic document for national development plans. It helps identify areas in which groundwater knowledge is as yet insufficient, and where further investigative studies should be undertaken. For a hydrogeological specialist it delivers basic information about work to be carried out for a groundwater exploration project (e.g. siting methods), and gives an indication about expected success rates for drilling new boreholes in certain areas. It definitely cannot be used to exactly locate new boreholes, since the scale is much too small and the resolution and accuracy of the information used to compile the Map is insufficient.

The International Legend allows the Map to be read in two different ways, from a distance and close up. From a distance of several metres, the overview of the Map area can be grasped and the distribution of aquifers, aquitards and aquicludes easily seen. For those wanting more detailed information, e.g. on the use of groundwater, there is, on closer scrutiny, a wealth of symbols indicating water supply and irrigation schemes, springs, boreholes and water control areas.

In particular, emphasis is placed on showing data characterising the groundwater flow systems. Springs are natural outflow areas and may sustain important wetlands. The way groundwater supplies these springs is shown, where sufficiently known, by arrows indicating the flow direction. In most of the country, particularly in the western mountainous areas, the boundaries of large, regional groundwater flow systems coincide with the boundaries of surface water catchments, and the groundwater divides are not shown. Where they are known to differ from the catchment boundaries, groundwater divides are shown as a line of purple circles. They can be used to delineate the groundwater flow systems within uniform hydrogeological units.

A wealth of man-made features that affect the natural groundwater systems is shown in red on the Map. All sites where groundwater is abstracted in appreciable quantities, such as water supply and irrigation schemes using groundwater are depicted. In the vicinity of these abstraction points, groundwater levels may be lowered locally or regionally. Inter-basin transfers from one catchment or groundwater basin to another are represented on the Map, because this information is important for water balance calculations. For instance, in the north and in the Windhoek area, appreciable amounts of water are imported into these groundwater basins via canals and pipelines.

Information on water quality is only considered if the groundwater is unfit for human consumption because of high concentrations of total dissolved solids, i.e. exceeding 2 600 mg/L. More detailed information on chemical parameters can be found on the set of groundwater quality maps published in 1982 (Huyser et al. 1982).

The inset maps, at even smaller scales, serve only as a rough overview of the theme displayed, but provide additional background information to understand and complement the features shown on the main Map. For example, the Map showing the borehole density in the country reflects the reliability of the productivity data in certain areas. Obviously, in areas with a low borehole density, the productivity information is based on fewer records and is thus less accurate.

Finally, the Map user is referred to the information provided in this book "Groundwater in Namibia – an explanation to the Hydrogeological Map". It contains a wealth of useful complementary information on the natural environment, rocks and groundwater, and includes aspects of groundwater use and protection pertinent to Namibia.

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Annex 1: Groundwater supply schemes operated by NamWater and municipalities

No	Scheme name	Lat	Long	Geology	Production (Tm³/a)	Depth (m)	Quality class
1	Aasvoelnes	-19,44000	20,11000	Kalahari	18	145	A
2	Ai-Ais	-27,90000	17,50000	Alluvium (Fish River)	58	15	A-B
3	Aminuis	-23,64000	19,37000	Sandstone, shale (Karoo)	86	186	B
4	Andara	-17,97200	21,26600	Kalahari (calcrete, sand)	10	55	D
5	Anichab	-20,95000	14,84000	Alluvium (Ugab River)	25	10-15	B
6	Anker	-19,77000	14,55000	Quartzite, granite (Huab Complex)	31	57-66	C
7	Aranos	-24,14700	19,11800	Sandstone (Karoo)	300	204-387	A
8	Ariamsvlei	-28,12000	19,84000	Meta-sediments (Nama Group)	40	100-120	B-C
9	Aroab	-26,80000	19,63000	Sandstone (Nama Group)	60	77-124	A
10	Aus	-26,66000	16,27400	Granite-gneiss (Namaqualand)	24	42-142	A-C
11	Bagani	-18,10900	21,65000	Kalahari	1	114	C-D
12	Berg Aukas	-19,50300	18,23600	Dolomite (Otavi Group, Damara)	700	92-98	B
13	Bergsig	-20,21000	14,06000	Basalt	2	12	A-B
14	Berseba	-25,99000	17,76000	Sandstone (Nama Group)	40	34-42	A
15	Bethanien	-26,50000	17,13000	Shale, limestone (Nama Group)	120	75	B-D
16	Brandwag	-19,68000	17,98000	Dolomite (Otavi Group, Damara)	0	15-60	B
17	Buinja	-17,86000	19,36000	Kalahari	6	57-79	A
18	Buitepos	-22,28000	19,99000	Tsumis Quartzite (Damara)	9	40-60	B
19	Bukalo	-17,72000	24,53000	Kalahari	70	40-54	B
20	Chinchimane	-17,98500	24,12400	Kalahari	30	50	B-C
21	Daan Viljoen	-22,54000	16,95000	Mica schist (Khomas, Damara)	60	76-125	B
22	Dordabis	-22,95000	17,66000	Quartzite (Rehoboth Sequence)	20	42-76	A-B
23	Epukiro Post 3	-21,58000	19,45000	Marble, quartzite, schist (Damara)	60	50-180	B-D
24	Epukiro Post 10	-21,52000	19,47000	Marble, quartzite, schist (Damara)	20	126-182	A-B
25	Ernst Meyer	-22,37000	19,40000	Kalahari & quartzite (Damara)	18	55-60	A
26	Erwee	-19,69000	14,30000	Quartzite, granite (Huab Complex)	30	58-65	B-C
27	Fransfontein	-20,21000	15,05000	Shale, dolomite, sandstone, limestone (Damara)	140	61-151	B
28	Gabis	-28,10000	18,61000	Namaqualand gneiss	19	56-86	C-D
29	Gainachas	-25,76000	17,71000	Sandstone (Nama Group)	3	32-39	A
30	Gibeon	-24,74000	17,89000	Sandstone (Dwyka, Karoo)	340	30-43	A
31	Gobabeb	-23,56000	15,04000	Alluvium (Kuiseb River)	2	30-40	B-D
32	Gobabis NE	-22,24000	19,11000	Damara Sequence	80		
	Black Nossob	-22,32000	18,92000	Damara Sequence	0	30	
	Grunental	-22,37200	18,39400	Damara Sequence	110	60-108	A
	South Station	-22,51000	18,98000	Damara Sequence	30	72-76	A
	Witvlei (> Gobabis)	-22,41000	18,47000	Damara Sequence	16	65	A
33	Goblenz	-20,09900	18,14500	Kalahari	800	100-450	A-B
34	Gochas	-24,75000	18,74000	Sandstone & shale (Karoo)	70	130-235	A
35	Grünau	-27,72000	18,38000	Granite (Namaqualand Complex)	10	58-160	B-D
36	Halali						
	Klein Halali	-19,05000	16,49000	Calcrete (Kalahari)	10	20-70	C
	Renosterkom	-19,09800	16,52000	Dolomite (Damara)	80	67-87	B
37	Henties Bay	-22,09000	14,29000	Alluvium (Omaruru Delta)	35	32-35	A
38	Hochfeld	-21,49000	17,85000	Damara Sequence	10	46-66	A
39	Kahenge	-17,68000	18,67000	Kalahari	26	38-40	A
40	Kalkfeld	-20,89000	16,19000	Meta-sediments, granite (Damara)	50	19-183	A-B
41	Kalkrand	-24,25000	17,26000	Basalt (Karoo)	100	65-77	B
42	Kamanjab						
	Town & Airport	-19,62000	14,84000	Intrusives, metased. (Huab Complex)	34	60-100	B-D
	Kalkrand	-19,64000	14,98000	Huab covered 10 m calcrete (Tertiary)	29	100-120	B
43	Karasburg	-28,00000	18,68000	Shale, dolerite (Karoo)	300	27-78	B
44	Karibib						
	Hälbichsbrunn	-21,96000	15,90000	Marble (Damara)	130	80-120	B-C
	Spes Bona	-21,78000	15,94000	Alluvium (Khan), limestone, shale (Damara)	0	31-76	
45	Karstland			Dolomite (Otavi Group, Damara)	10		B
46	Kayengona	-17,89000	19,88000	Kalahari	140	50-60	A
47	Khorixas	-20,38000	14,96000	Calcrete, dolomite (Damara)	700-1.6	31-150	B
48	Koes	-25,93000	19,12000	Sandstone (Ecca Group, Karoo)	70	43-70	B
49	Koichab	-26,20000	15,87000	Sand, gravel, clay (Tertiary)	600-1.0	59-107	A
50	Kosis	-26,71000	17,32000	Sandstone, shale, limestone (Nama Gr.)	45	60-70	A-B
51	Kriess	-25,00000	18,16000	Sandstone (Karoo)	10	80-90	A
52	Kuiseb	-23,19000	14,66000	Alluvium (Kuiseb River)	5.500	15-50	A-B
	Dorop						
	Rooibank						
	Swartbank						

No	Scheme name	Lat	Long	Geology	Production (Tm^3/a)	Depth (m)	Quality class
53	Kwakwas	-23,21000	16,90000	Quartzite, schist (Rehoboth Sequence)	No info	79-104	A-B
54	Leonardville	-23,50300	18,79000	Sandstone, shale (Karoo)	60	188-280	A-B
55	Maltahöhe	-24,81000	16,99000	Quartzite (Nama Group)	200	31-46	C
56	Mangetti Duin	-19,52000	19,73000	Kalahari	40	180-197	A
57	Maroelaboom	-19,25000	18,80000	Kalahari	4	147	B
58	M'Kata	-19,50000	19,63000	Kalahari	9	170	A
59	Mpunguvlei	-17,67000	18,23000	Kalahari	20	86-90	D
60	Mupini	-17,86000	19,63000	Kalahari	5	50-57	C
61	Namutoni	-18,80000	17,04000	Kalahari	150	39-43	B
62	Nei Neis	-21,47000	15,04000	Alluvium (Omaruru River)	330	12-28	A-C
63	Nkurenkuru	-17,63000	18,62000	Kalahari	20	40-60	
64	Nyangana	-18,02000	20,68000	Kalahari	80		
65	Oamites	-22,98000	17,07000	Marble (Damara)	250	100-150	No info
66	Okaukuejo	-19,18000	15,92000	Kalahari (calcrete)	250	10-80	B
67	Okombahe	-21,35000	15,40000	Alluvium (Omaruru River)	380	25-26	A
68	Okondjatu	-20,98000	18,23000	Damara under Kalahari	70	98-100	B
69	Omatako	-19,44000	19,22000	Kalahari	20	161-184	B
70	Omatako Dam	-21,14000	17,17000	Sandstone, shale (Karoo)	4	55-90	B-D
71	Ombika	-19,33000	15,94000	Dolomite, limestone (Otavi, Damara)	12	20-130	B
72	Omdel	-22,09000	14,29000	Alluvium (Omaruru Delta)	5.500	50-100	B
73	Omega	-17,89000	22,15000	Kalahari	115	70-90	B
74	Ondekaremba	-22,48000	17,42000	Khomas schist (Damara)	4	96-125	B
75	Onderombapa	-23,15000	19,56000	Sandstone, shale (Karoo)	4	93-96	A
76	Opuwo	-18,06000	13,85000				
	SE wellfield	-18,15000	13,95000	Otavi Group, Damara	25	90-120	B
	NW wellfield	-18,04000	13,82000	Karoo (Dwyka) / calcrete	780	56-110	C-D
77	Oshivelo	-18,62000	17,17000	Kalahari (sand, shale)	300	68-74	B
78	Osire	-21,08000	17,37000	Omingonde Fm (Karoo)	55	57-77	A-B
79	Otavi	-19,64000	17,35000	Limestone, dolomite (Otavi, Damara)	500	60-61	A-B
80	Otjimbingwe	-22,35200	16,13600	Alluvium (Swakop River)	280	12	A-C
81	Otjinene	-21,14000	18,79000	Damara under Kalahari	150	63-125	A-C
82	Otjiwarongo	-20,46000	16,64000	Marble (Damara)	1.800	66-185	B
	Otjituuo	-19,44800	18,21000	Dolimite (Berg Aukas formasie)	900	85-100	A
83	Otjovasandu	-19,25000	14,51000	Metamorphosed lava (Khoabendus)	10	61	B-C
84	Ovitoto	-21,91000	17,10000	Damara Sequence	40	32-38	B
85	Plessisplaas	-21,71000	19,04000	Kalahari, Gamsberg granite	10	56-82	A
86	Rietfontein	-21,90400	20,91800	Kamtsas Fm (Damara)	140	48-109	C
87	Rooidaghek	-19,25000	19,27000	Kalahari	10	180	
88	Runduhek	-18,78700	18,94200	Kalahari	30	250	
89	Rupara	-17,84000	19,08000	Kalahari	10	77-82	A
90	Sambiu	-17,91000	20,03000	Kalahari	30	60-70	A
91	Schlip	-24,04300	17,13100	Limestone, dolomite, shale (Nama)	230	43-104	B
92	Seeis	-22,45000	17,62000	Alluvium (Seeis River)	30	12-15	No info
93	Sesfontein	-19,12000	13,61000	Dolomite, phyllite (Damara)	20	36-51	A-B
94	Spitzkoppe	-21,85000	15,20000	Granite, schist (Damara)	13	60-92	C-D
95	Stampriet	-24,34200	18,40900	Sandstone, shale (Karoo)	60	84-101	A
96	Terrace Bay	-20,18900	13,20100	Alluvium (Uniab River)	17	10-20	A-D
97	Tondoro	-17,77000	18,79000	Kalahari	70	65-68	A
98	Tses						
	Old scheme	-25,89000	18,11000	Shale (Dwyka, Nama Group)	30	47-109	A-C
	New boreholes	-25,92000	17,94000	Shale (Dwyka, Nama Group)	0	57-100	B-C
99	Tsintsabis	-18,78000	17,96000	Kalahari	30	31-93	B
100	Tsumkwe	-19,59000	20,50000	Kalahari	55	20-35	A-C
101	Tubussis	-21,54800	15,46200	Schist, quartzite (Damara)	20	13-110	B-C
102	Usakos	-21,99200	15,60100		285	15-100	A-B
	Khan River			Alluvium (Khan River)			
	Aroab River			Calcrete & Onguati marble			
103	Warmbad	-28,44100	18,74200	Namaqualand granite-gneiss complex	25	107-110	C-D
104	Witvlei	-22,41000	18,50000	Quartzite, limestone (Damara)	140	31-38	B-D
Municipal schemes							
105	Windhoek	-22,59000	17,08000	Auas quartzites	2.000	77-305	A
106	Omaruru	-21,41000	15,95000	Alluvium (Omaruru River)	1.000	12-16	A
107	Tsumeb	-19,25000	17,71000	Dolomite	2.000	130-200	A
108	Outjo	-20,11000	16,16000	Dolomite	800	90-100	A
109	Grootfontein	-19,56000	18,11000	Dolomite	2.000	50-70	A

Annex 2: Selected representative boreholes

Latitude	Longitude	WW no	Depth [m]	Water level [m bgl]	Yield [m^3/h]	Water quality	Aquifer host rock
-17.50013	24.35257	37113	49	6	22	C	Kalahari
-17.50590	12.79480	33962	39	8	4	A	Quartzite
-17.56111	16.35397	37070	259	20	18	C	Kalahari (Very Deep Aquifer)
-17.60965	12.94160	36681	74	-	0	-	Gneiss
-17.64612	24.16922	36622	70	14	19	C	Kalahari
-17.68162	24.46502	37111	39	4	22	C	Kalahari
-17.69023	23.42113	36479	68	24	19	A	Kalahari
-17.70410	12.75600	33963	59	17	1	A	Gneiss
-17.70710	24.03052	36451	69	23	11	B	Kalahari
-17.78010	16.84440	36867	200	55	13	A	Kalahari
-17.82223	23.39272	36502	61	31	9	A	Kalahari
-17.85707	23.71302	36543	73	16	10	B	Kalahari
-17.88680	15.95620	9124	668	-	10	-	Kalahari, Karoo
-17.88735	24.19542	36575	27	9	-	B	Kalahari
-17.89303	18.28392	39962	101	-	1	-	Kalahari
-17.95050	23.47782	36529	76	29	-	B	Kalahari
-17.97130	13.85610	33969	70	16	3	B	Shale
-17.97300	14.02870	33964	71	40	-	A	Dolomite
-17.98600	13.81840	33958	104	-	0	-	Shale
-17.99600	13.65900	33959	108	23	3	A	Shale
-18.06190	12.76660	33972	103	-	0	-	Quartzite, shale
-18.08562	23.37620	36540	59	7	-	B	Kalahari
-18.20398	19.48798	39964	72	-	22	-	Kalahari
-18.24922	21.03687	39961	81	-	13	-	Kalahari
-18.26565	19.92525	39966	70	-	13	-	Kalahari
-18.34710	16.56610	8191	101	15	10	D	Kalahari
-18.35210	13.89570	33966	70	38	7	A	Dolomite
-18.36967	19.10807	39965	120	-	4	-	Kalahari
-18.43290	13.93950	33967	100	62	1	A	Siltstone
-18.52083	16.77250	2731	244	Artesian	100	D	Kalahari (Oshivelo Artesian Aquifer)
-18.58667	14.25833	36680	121	3	4	A	Calcrete, mudstone, sandstone
-18.77930	12.94510	33975	15	7	26	-	Gneiss
-18.97460	14.15555	35489	56	31	7	A	Calcrete, clay
-18.97460	14.15555	35490	154	32	15	A	Calcrete, clay, shale
-18.99536	17.60146	39980	398	11	2	B	Shale, mudstone (Karoo sequence)
-18.99643	16.40460	9581	32	Artesian	8	D	Dolomite (Tsumeb Subgroup)
-19.01942	14.47157	35827	101	13	150	B	Dolomite (Abenab Subgroup)
-19.08487	14.04905	35491	183	56	11	A	Calcrete, clay, shale
-19.10972	15.21255	37229	63	11	-	B	Kalahari (Limestone of Unconfined Kalahari Aquifer)
-19.21389	16.05861	3617	46	15	-	C	Kalahari (Limestone of Unconfined Kalahari Aquifer)
-19.30245	18.07460	40000	400	66	25	B	Dolomite, limestone (Abenab subgroup)
-19.33841	17.18271	39984	335	12	12	B	Quartzite, shale (Mulden group)
-19.38713	14.57475	37180	63	32	-	B	Khoabendus Formation
-19.41740	17.61896	39991	140	53	1	B	Quartzite (Nosib formation)
-19.41843	17.88354	39972	85	37	2	B	Gneiss (Grootfontein basement complex)
-19.52147	14.36407	4245	49	37	3	D	Gneiss
-19.99097	19.73580	39967	117	-	23	-	Kalahari
-20.02960	18.19470	37741	462	33	33	B	Kalahari
-20.13264	20.14354	39913	225	138	0	-	Kalahari
-20.15293	20.79700	39909	201	7	1	B	Dolomite
-20.15900	16.89290	30643	78	5	144	A	Marble
-20.16322	14.85734	7647	31	5	8	C	Gneiss

Latitude	Longitude	WW no	Depth [m]	Water level [m bgl]	Yield [m^3/h]	Water quality	Aquifer host rock
-20.21846	14.07537	20020	58	6	2	B	Basalt
-20.25040	16.76110	29494	102	36	36	A	Marble
-20.34668	14.46168	39938	34	23	-	D	Gneiss
-20.36964	15.11598	30815	95	11	0	C	Schist
-20.46185	20.78952	39912	157	120	5	B	Calcrete, dolomite
-20.53340	17.36987	39910	171	-	0	-	Clay, siltsone, mudstone, schist
-20.54140	14.49924	6393	33	22	5	D	Granite
-20.67605	20.81943	39907	165	144	1	-	Kalahari
-20.87434	19.13697	39979	201	-	0	-	Sandstone, marble
-20.94361	17.43833	34684	120	75	2	A	Sandstone
-21.79917	18.87472	35206	102	1	100	A	Kalahari, quartzite (Eskadron)
-21.82020	15.56140	22159	27	7	8	A	Alluvium of Khan River with bedrock of granite, schist
-21.83023	20.47874	39906	201	-	0	A	Quartzite
-21.91410	14.46020	22194	100	28	70	A	Alluvium of Omaruru Delta
-22.08480	19.89810	39905	177	-	0	A	Kalahari
-22.14333	19.07555	35224	120	23	34	A	Kalahari, quartzite
-22.15358	17.11150	39908	99	6	1	C	Schist
-22.19138	19.04306	35229	102	24	82	A	Kalahari, quartzite
-22.28778	19.22778	35203	108	26	68	A	Quartzite
-22.36806	19.05222	35215	102	22	39	A	Quartzite
-23.25415	18.98668	39839	256	58	8	-	Sandstone (Auob member)
-23.34070	14.77480	20146	33	10	74	A	Alluvium of Kuiseb River
-23.40049	19.62557	39846	204	59	20	C	Sandstone (Auob member)
-23.40098	19.62489	39845	53	45	0	-	Basalt (Kalkrand basalt)
-23.40105	19.62621	39847	356	10	12	-	Sandstone (Nossob member)
-23.64747	18.38873	39840	131	17	3	A	Sandstone (Auob member)
-23.64808	18.38871	39841	209	7	3	-	Sandstone (Nossob member)
-23.88778	18.03833	34572	39	13	34	A	Basalt
-23.92722	18.04667	34534	54	3	6	A	Basalt
-23.96917	18.03944	34569	44	6	8	A	Basalt
-24.00194	18.21500	39857	141	2	45	A	Sandstone (Auob member)
-24.04592	18.79340	39842	102	19	2	-	Calcrete (Rietmond formation)
-24.04792	18.79312	39843	253	16	20	A	Sandstone (Auob member)
-24.04858	18.79614	39844	409	Artesian	0	A	Sandstone (Nossob member)
-24.32842	18.39794	39848	187	Artesian	1	-	Sandstone (Nossob member)
-24.79963	19.33457	39851	385	Artesian	-	-	Sandstone (Nossob member)
-24.80009	19.33483	39849	169	102	3	-	Kalahari
-24.80059	19.33520	39850	273	104	4	B	Sandstone (Auob member)
-25.00056	17.85667	33749	50	2	10	D	Carbonaceous shale
-25.09250	17.50889	34260	90	45	6	A	Sandstone
-25.19530	17.35000	33761	154	130	1	B	Sandstone
-25.29117	18.41650	39853	250	22	0	-	Sandstone (Nossob member)
-25.29163	18.41678	39852	55	10	7	-	Kalahari
-25.34940	17.68970	33784	86	12	4	A	Sandstone
-25.45174	19.43373	39855	250	172	-	D	Sandstone (Auob member)
-25.46028	19.42444	39854	129	60	0	C	Kalahari
-25.46148	19.43324	39856	346	20	-	D	Sandstone (Nossob member)
-25.48000	17.48972	34692	50	16	-	A	Sandstone
-25.51722	17.53556	34695	93	37	1	B	Sandstone
-25.73417	17.39611	33739	250	192	1	B	Sandstone
-26.21889	18.81250	34682	44	9	9	A	Sandstone
-26.33420	17.44670	33742	250	209	1	B	Sandstone

Annex 3: Irrigation schemes using groundwater

Scheme Name	Latitude	Longitude	Cons./Ha (m^3/a)	1999 (Mm^3/a)	Basin	Main crops
Aalborg	-19.15	17.85	15000	0.0450	Cuvelai	Vegetables
Abenab	-19.29	18.09	9000	0.1800	Cuvelai	Maize
Adrianople	-24.32	19.39	15000	0.0900	Nossob	
A'hingas	-25.39	18.63	18000	0.0000	Auob	
Ai-ais	-23.10	18.68	15000	0.0300	Nossob	
Areams	-23.86	19.05	17908	0.0537	Nossob	Lucerne
Awadoab	-24.00	18.95	15000	0.0450	Nossob	
Badenhorst	-23.36	18.70	15000	0.0600	Nossob	
Berg Aukas	-19.51	18.26	15000	0.1200	Omatako	Vegetables
Bernafay	-24.61	18.55	20000	0.2000	Auob	Vegetables, citrus
Blakeway	-22.64	14.67	20000	0.0200	Swakop	
Boomplaas	-24.56	18.53	15000	0.1500	Auob	Maize, lucerne
Cleopatra	-24.09	19.07	14086	0.0563	Nossob	Lucerne
Dawn	-19.50	18.10	15000	0.0150	Omatako	Vegetables
De Duinen	-24.59	18.45	15000	0.0750	Auob	
De Jager	-23.21	18.74	15000	0.0450	Nossob	
Die Vlakte	-19.47	14.89	10000	0.0300	Huab	Vegetables
Dobbin	-24.29	18.50	27138	0.5428	Auob	Vegetables, melons
Donnersberg	-23.19	18.65	25629	0.0769	Nossob	Lucerne
Drimiopsis	-22.09	19.06	10000	0.0400	Nossob	Vegetables
Eahero	-21.45	17.95	10000	0.1000	Omatako	Vegetables
Eendrag	-21.27	17.82	10000	0.0900	Omatako	Maize, vegetables
Eersbegin	-20.14	14.52	12000	0.3600	Huab	Dates
Eerstbegin	-24.36	18.58	20299	0.0609	Auob	Vegetables, prickly pears
Eirup	-24.22	18.41	22260	0.1336	Auob	Citrus, lucerne
Excelsior	-19.01	17.94	10000	0.0700	Cuvelai	Vegetables, maize
Fricourt	-24.55	18.66	14858	0.2972	Auob	Lucerne, table grapes
Friedrichsruhe	-19.16	17.81	7603	0.2281	Cuvelai	Maize
Gabis	-28.28	18.57	18000	0.0180	Orange	Fodder, vegetables
Gainatseb	-20.29	15.23	15000	0.0750	Huab	Citrus
Galenbeck	-24.16	18.13	18000	0.0000	Auob	
Galton	-23.32	18.68	15000	0.0450	Nossob	
Geinkous	-23.40	18.71	15000	0.0450	Nossob	
Georgia	-23.29	18.66	24000	0.0240	Nossob	Lucerne
Glave	-24.18	18.65	28290	0.4244	Auob	Table grapes
Goanikontes no 28/b	-22.67	14.84	9840	0.0492	Swakop	Dates, lucerne, fodder
Goanikontes Oos no 59	-22.67	14.82	8000	0.0240	Swakop	Dates, lucerne, prickly pears, asparagus, fodder
Gross Nabas	-24.50	18.55	29531	0.1772	Auob	Vegetables, melons
Guinas (Henning Farm)	-19.25	17.39	15000	0.4500	Cuvelai	Maize, wheat, cotton
Guinas vlei (Erasmus Farm)	-19.24	17.23	15000	0.0300	Cuvelai	Vegetables
Gunchab	-24.15	18.56	13200	0.0792	Auob	
Hartebeesteich Noord	-21.38	17.86	10000	0.0150	Omatako	Vegetables
Hartebeesteich Suid	-21.43	17.87	12000	0.0600	Omatako	Olives
Hartebeestloop	-24.36	18.75	7577	0.0379	Auob	
Heidelberg	-19.09	17.75	10754	0.1613	Cuvelai	
Hiebis Ost	-19.09	17.81	15000	0.0900	Cuvelai	Vegetables, citrus
Hoagosgeis	-23.79	18.95	15000	0.0450	Nossob	Lucerne
Hoogenhout	-24.37	18.36	24000	0.0960	Auob	Lucerne, table grapes
Huttenhof	-19.48	17.19	8073	0.2826	Cuvelai	Maize
Imkerhof	-21.23	17.74	10000	0.1000	Omatako	Cotton
Kameelboom	-24.25	18.73	12108	0.0726	Auob	Maize
Kameelpoort	-23.29	18.79	15000	0.0450	Nossob	
Klein Birkenfels	-22.64	14.75	18000	0.0000	Swakop	
Klein Hutte	-24.59	18.69	18000	0.0180	Auob	Lucerne, oats, seet potatoes
Klein Nabas West	-24.55	18.49	18000	0.2880	Auob	Lucerne, maize
Kombat	-19.76	17.68	15000	1.5000	Ugab	Maize, wheat
Kosis	-25.01	17.34	18000	0.0063	Fish	Fodder, vegetables
Kowarib	-19.26	13.75	4778	0.0860	Hoanib	Wheat, maize, tabacco, citrus
Kristall	-21.45	16.01	20000	0.1000	Omaruru	Vineyard, asparagus
Langverwacht	-25.02	18.52	15000	0.0450	Auob	
Lidfontein	-24.07	18.25	18000	0.0000	Auob	
Ludwigshaven	-19.15	17.78	20000	2.4000	Cuvelai	Maize, vegetables, citrus
Maitland	-21.31	17.75	10000	0.0500	Omatako	Vegetables
Mangetti Dune (Tsumkwe)	-18.50	17.66	10000	0.0500	Cuvelai	Vegetables

Scheme Name	Latitude	Longitude	Cons./Ha (m^3/a)	1999 (Mm^3/a)	Basin	Main crops
Mannheim farms and plots	-19.15	17.74	20000	3.0000	Cuvelai	Maize, wheat, lucerne, citrus, vegetables
Mara (Halifax)	-24.81	16.69	10000	0.0500	Fish	Vegetables
Middelplaats	-24.34	18.67	24529	0.5396	Auob	Vegetables, maize, melons
Nabas Ost	-24.50	18.66	24000	0.4800	Auob	Lucerne
Nadine	-22.65	14.70	18000	0.0000	Swakop	
Namatanga	-18.31	14.44	10000	0.0500	Cuvelai	Vegetables
Noasanabis	-23.46	18.82	18000	0.0180	Nossob	Lucerne, vegetables
Nunib	-24.20	18.57	11024	0.1764	Auob	Maize, wheat
Nuwe Coenbritz	-23.87	18.88	7256	0.0218	Nossob	Lucerne, vegetables
Nuwe Manie	-23.83	19.00	18487	0.0555	Nossob	Lucerne
Oanob river plots (Rehoboth)	-23.33	17.11			Oanob	
Okamahapu	-21.53	17.71	10000	0.1000	Omatako	Vegetables
Okaokasjoti	-21.40	16.03	10000	0.1200	Omaruru	Vegetables
Okongeama	-21.56	17.94	12000	0.0240	Omatako	Olives
Okoronyama	-21.32	16.09	10000	0.0200	Omaruru	Fodder
Olifants fontein	-19.45	18.02	20000	0.0000	Omatako	Vegetables, citrus
Omatako Dam (Mcloud)	-21.05	16.95	24000	0.4800	Omatako	Lucerne
Omupanda	-21.49	17.96	22000	0.0220	Omatako	Citrus
Orab	-24.74	17.91	15000	0.0750	Fish	
Osterode Nord	-24.40	18.42	24025	0.3604	Auob	Lucerne, maize, vegetables, melon
Osterode Sud	-24.42	18.47	21782	0.2178	Auob	Lucerne, vegetables
Otavi Farm	-19.68	17.39	12000	0.3600	Ugab	Maize, wheat
Otavi Fontein	-19.67	17.43	10160	0.2032	Ugab	Vegetables, citrus
Otjozondu Oos	-21.26	17.89	10000	0.0100	Omatako	Vegetables
Outjo farms	-20.14	16.25	15000	0.6900	Ugab	Vegetables
Palmenhorst	-22.69	14.90	18000	0.0000	Swakop	
Portion 11 of Omburo	-21.27	16.20	9550	0.0955	Omaruru	Fodder
Portion 3 of Omburo	-21.29	16.17	12000	0.0720	Omaruru	
Portion 6 & 9 Okoronyama	-21.32	16.11	12512	0.3754	Omaruru	Lucerne, citrus
Portion c of Kakombo	-21.36	15.98	11740	0.0117	Omaruru	Citrus, vegetables
RC Mission Aminuis	-23.69	19.44	10000	0.0300	Nossob	
RC Mission Waldfrieden	-21.39	16.10	18000	0.0360	Omaruru	Vegetables, lucerne
Remainder of Omburo	-21.24	16.24	20675	0.0827	Omaruru	Lucerne
Richthoven	-22.64	14.71	15000	0.0450	Swakop	Asparagus
Rietfontein Farm	-19.79	17.78	20000	1.6600	Omatako	Maize, lucerne
Rössing Uranium	-22.51	15.06	24781	0.2974	Swakop	Asparagus, vegetables
Ruhleben	-22.64	14.69	20333	0.0610	Swakop	
Schifloodage	-24.63	18.71	15000	0.0150	Auob	Lucerne, prickley pears, vegetables
Schurfpenz	-24.21	18.27	18000	0.0000	Auob	
Scott	-19.09	17.87	15000	0.1800	Cuvelai	Vegetables, citrus
Sesfontein	-19.15	13.59	12000	0.3600	Hoanib	Wheat, maize, tabacco, citrus
Skoonheid	-21.54	19.15	10000	0.0200	Okavango Delta	Vegetables
Sommerville	-23.73	18.94	10000	0.0500	Nossob	Maize, vegetables
Spes Bona	-21.35	18.13	22000	0.0880	Omatako	Citrus
Sponholz	-24.65	18.53	23270	0.1164	Auob	Lucerne
Stampriet	-24.32	18.42	25000	2.0000	Auob	Table grapes, vegetables, lucerne, melons
Swakopaue	-22.64	14.63	9200	0.0046	Swakop	
Swartmodder	-24.31	18.19	18000	0.0000	Auob	
Tannenhof	-22.64	14.72	18000	0.0000	Swakop	
Three Sisters	-22.65	14.69	24000	0.1200	Swakop	Lucerne
Toekoms	-24.02	18.88	18000	0.0180	Nossob	Lucerne, prickley pears, vegetables
Tsumeb town and townlands	-19.26	17.71	24000	4.8000	Cuvelai	Lucerne
Uitkomst no 78 (Floodeischmann)	-22.64	14.65	24000	0.1920	Swakop	Lucerne
Urikuribus	-24.73	18.80	18000	0.0000	Auob	
Vaalbank	-23.93	18.87	18000	0.0000	Nossob	
Virginia	-23.24	18.65	24000	0.0240	Nossob	Lucerne
Walroda	-19.39	17.47	15000	0.0300	Ugab	Vegetables
Warmquelle/Ongongo	-19.17	13.81	12000	0.1920	Hoanib	Wheat, maize, tobacco, citrus
Welgevonde	-23.97	18.88	6080	0.0304	Nossob	Lucerne, vegetables
Westfalen	-23.66	18.02	20000	0.1600	Auob	Citrus, vegetables
Witkranz	-24.44	18.53	8000	0.0560	Auob	Lucerne, vegetables, cotton, maize
Wolfputz	-23.91	18.12	18000	0.0000	Auob	

Annex 4: Comparison of selected guideline values for drinking water quality

Parameter and Expression of the results			**WHO** Guidelines for Drinking-Water Quality 2nd edition 1993		**Proposed Council Directive** of 28 April 1995 (95/C/13-1/03) EEC	**Council Directive of 15 July 1980** relating to the quality intended for human consumption 80/778/EEC		U.S. EPA Drinking Water Standards and Health Advisories Table December 1995		**Namibia, Department of Water Affairs** Guidelines for the evaluation of drinking-water for human consumption with reference to chemical, physical and bacteriological quality July 1991			
				Guideline Value (GV)	Proposed Parameter Value	Guide Level (GL)	Maximum Admissible Concentration (MAC)		Maximum Contaminant Level (MCL)	Group A Excellent Quality	Group B Good Quality	Group C Low Health Risk	Group D Unsuitable
Temperature	t	° C		-	-	12	25		-	-	-	-	-
Hydrogen ion concentration	pH, 25° C	-	R	< 8.0	6.5 to 9.5	6.5 to 8.5	10		-	6.0 to 9.0	5.5 to 9.5	4.0 to 11.0	< 4.0 to > 11.0
Electronic conductivity	EC, 25° C	mS/m		-	280	45	-		-	150	300	400	> 400
Total dissolved solids	TDS	mg/l	R	1000	-	-	1500		-	-	-	-	-
Total Hardness	$CaCO_3$	mg/l		-	-	-	-		-	300	650	1300	> 1300
Aluminium	Al	µg/l	R	200	200	50	200	S	50-200	150	500	1000	> 1000
Ammonia	NH_4^+	mg/l	R	1.5	0.5	0.05	0.5		-	1.5	2.5	5.0	> 5.0
	N	mg/l		1,0		0.04	0.4		-	1.0	2.0	4.0	> 4.0
Antimony	Sb	µg/l	P	5	3	-	10	C	6	50	100	200	> 200
Arsenic	As	µg/l	P	10	10	-	50	C	50	100	300	600	> 600
Barium	Ba	µg/l		700	-	100	-	C	2000	500	1000	2000	> 2000
Beryllium	Be	µg/l		-	-	-	-	C	4	2	5	10	> 10
Bismuth	Bi	µg/l		-	-	-	-		-	250	500	1000	> 1000
Boron	B	µg/l		300	300	1000	-		-	500	2000	4000	> 4000
Bromate	BrO_3^-	µg/l		-	10	-	-	P	10	-	-	-	-
Bromine	Br	µg/l		-	-	-	-		-	1000	3000	6000	> 6000
Cadmium	Cd	µg/l		3	5	-	5	C	5	10	20	40	> 40
Calcium	Ca	mg/l		-	-	100	-		-	150	200	400	> 400
	$CaCO_3$	mg/l		-	-	250	-		-	375	500	1000	> 1000
Cerium	Ce	µg/l		-	-	-	-		-	1000	2000	4000	> 4000
Chloride	Cl^-	mg/l	R	250	-	25	-	S	250	250	600	1200	> 1200
Chromium	Cr	µg/l	P	50	50	-	50	C	100	100	200	400	> 400
Cobalt	Co	µg/l		-	-	-	-		-	250	500	1000	> 1000
Copper	Cu	µg/l	P	2000	2	100	-	C	TT##	500	1000	2000	> 2000
after 12 hours in pipe[1]		µg/l		-	-	3000[1]	-	S	1000	-	-	-	-
Cyanide	CN^-	µg/l		70	50	-	50	C	200	200	300	600	> 600
Fluoride	F^-	mg/l		1.5	1.5	-	at 8 to 12 ° C: 1.5	C	4	1.5	2.0	3.0	> 3.0
		mg/l		-	-	-	at 25 to 30 ° C: 0.7	P, S	2	-	-	-	-
Gold	Au	µg/l		-	-	-	-		-	2	5	10	> 10
Hydrogen sulphide	H_2S	µg/l	R	50	-	-	undetectable organoleptically		-	100	300	600	> 600
Iodine	I	µg/l		-	-	-	-		-	500	1000	2000	> 2000
			P: Provisional R: May give reason to complaints from consumers					C: Current; P: Proposed; S: Secondary; T#: Treatment technique in lieu of numeric MCL; TT##: Treatment technique triggered at action level of 1300 µg/l					

Parameter and Expression of the results			**WHO** Guidelines for Drinking-Water Quality 2nd edition 1993		**Proposed Council Directive** of 28 April 1995 (95/C/13-1/03) EEC	**Council Directive of 15 July 1980** relating to the quality intended for human consumption 80/778/EEC		U.S. EPA Drinking Water Standards and Health Advisories Table December 1995		**Namibia, Department of Water Affairs** Guidelines for the evaluation of drinking-water for human consumption with reference to chemical, physical and bacteriological quality July 1991			
				Guideline Value (GV)	Proposed Parameter Value	Guide Level (GL)	Maximum Admissible Concentration (MAC)		Maximum Contaminant Level (MCL)	Group A Excellent Quality	Group B Good Quality	Group C Low Health Risk	Group D Unsuitable
Iron	Fe	µg/l	R	300	200	50	200	S	300	100	1000	2000	> 2000
Lead	Pb	µg/l		10	10	-	50	C	TT#	50	100	200	> 200
Lithium	Li	µg/l		-	-	-	-		-	2500	5000	10000	> 10000
Magnesium	Mg	mg/l		-	-	30	50		-	70	100	200	> 200
	$CaCO_3$	mg/l		-	-	7	12		-	290	420	840	> 840
Manganese	Mn	µg/l	P	500	50	20	50	S	50	50	1000	2000	> 2000
Mercury	Hg	µg/l		1	1	-	1	C	2	5	10	20	> 20
Molybdenum	Mo	µg/l		70	-	-	-		-	50	100	200	> 200
Nickel	Ni	µg/l		20	20	-	50		-	250	500	1000	> 1000
Nitrate *	NO_3^-	mg/l		50	50	25	50		45	45	90	180	> 180
	N	mg/l		-	-	5	11	C	10	10	20	40	> 40
Nitrite *	NO_2^-	mg/l	P	3	0,1	-	0,1		3	-	-	-	-
	N	mg/l		-	-	-		C	1	-	-	-	-
Oxygen, dissolved	O_2	% sat.		-	50	-	-		-	-	-	-	-
Phosphorus	P_2O_5	µg/l		-	-	400	5000		-	-	-	-	-
	PO_4^{3-}	µg/l		-	-	300	3350		-	-	-	-	-
Potassium	K	mg/l		-	-	10	12		-	200	400	800	> 800
Selenium	Se	µg/l		10	10	-	10	C	50	20	50	100	> 100
Silver	Ag	µg/l		-	-	-	10	S	100	20	50	100	> 100
Sodium	Na	mg/l	R	200	-	20	175		-	100	400	800	> 800
Sulphate	SO_4^{2-}	mg/l	R	250	250	25	250	S	250	200	600	1200	> 1200
Tellurium	Te	µg/l		-	-	-	-		-	2	5	10	> 10
Thallium	Tl	µg/l		-	-	-	-	C	2	5	10	20	> 20
Tin	Sn	µg/l		-	-	-	-		-	100	200	400	> 400
Titanium	Ti	µg/l		-	-	-	-		-	100	500	1000	> 1000
Tungsten	W	µg/l		-	-	-	-		-	100	500	1000	> 1000
Uranium	U	µg/l		-	-	-	-	P	20	1000	4000	8000	> 8000
Vanadium	V	µg/l		-	-	-	-		-	250	500	1000	> 1000
Zinc	Zn	µg/l	R	3000	-	100	-	S	5000	1000	5000	10000	> 10000
after 12 hours in pipe		µg/l		-	-	5000	-		-	-	-	-	-

* $C_{NO3} / GV_{NO3} + C_{NO2} / GV_{NO2}$ 1

P: Provisional
R: May give reason to complaints from consumers

C: Current; P: Proposed; S: Secondary;
T#: Treatment technique in lieu of numeric MCL;
TT##: Treatment technique triggered at action level of 1300 µg/l

Glossary

a Annum (lat.), year.

a BP Years before present (= 1950).

Acrisol Soil having a B horizon with illuvial accumulation of clay and low base saturation.

aeolian Pertinent to the action of wind.

Ag Silver.

Al Aluminium.

Alluvium Sediments deposited by flowing rivers. Depending on the location in the floodplain in the river, different sized sediments are deposited.

Amphibolite High grade metamorphic rock.

AN Andoni Formation.

Anion exchange Ion exchange process in which anions in solution are exchanged for other anions from an ion exchanger.

Aquiclude A geologic formation, group of formations, or part of a formation through which virtually no water moves.

Aquifer Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water to boreholes or springs.

Aquifer, confined An aquifer that is overlain by a confining bed. The confining bed has a significantly lower hydraulic conductivity than the aquifer.

Aquifer, perched Aquifer containing isolated bodies of groundwater suspended above water table.

Aquifer, semi-confined An aquifer confined by a low permeability layer that permits water to flow slowly through it. During pumping of the aquifer, recharge to the aquifer can occur across the confining layer. Also known as a leaky artesian or leaky confined aquifer.

Aquifer, unconfined Aquifer where the water table is exposed to the atmosphere through openings in the overlying materials.

Aquifer test A test involving the withdrawal of measured quantities of water from or the addition to, a well and the measurement of the resulting changes in head in the aquifer both during and after the period of discharge or addition.

Aquitard A saturated, but poorly permeable bed, formation, of group of formations that does not yield water freely to a well or spring. However, an aquitard may transmit appreciable water to and from adjacent aquifers.

Arenosol Weakly developed, deep sandy soil.

Argillite, argilliceous Clayey sediment, compacted.

Arkose A sandstone containing 25 % or more of feldspars. Usually derived from disintegrated acid igneous rock of granitoid texture.

Artesian well A well deriving its water from an confined aquifer in which the water level stands above the ground surface; synonymous with flowing artesian well.

Artificial recharge The process by which water can be injected or added to an aquifer. Dug basins, drilled wells, or simply the spread of water across the surface are all means of artificial recharge.

As Arsenic.

asl Above sea level.

Atm Atmosphere(s).

Basalt A general term for dark-coloured iron- and magnesium rich igneous rocks, commonly extrusive, but locally intrusive. It is the principle rock making up the ocean floor.

Bedrock A general term for the rock, usually solid, that underlies soil or other unconsolidated material.

Bentonite A colloidal clay, largely made up of the mineral sodium montmorillonite, a hydrated aluminium silicate.

bgl Below ground level.

BGR Bundesanstalt für Geowissenschaften und Rohstoffe/ Federal Institute for Geosciences and Natural Resources, Hannover, Germany.

BMZ Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung / Federal Ministry for Economic Cooperation and Development, Bonn/Berlin, Germany.

Borehole development The process by which a borehole is pumped or surged to remove any fine material that may be blocking the well screen or the aquifer outside the well screen.

Brackish 1 000 to 10 000 mg/L TDS or 150 to 1 500 mS/m EC, or Group B to C quality.

C Capita.

°C Grad Celsius, dimension of temperature.

Ca Calcium.

Calcisol Soil characterised by calcium carbonate ($CaCO_3$).

Calcrete Carbonates, precipitated from rain water or groundwater (see Box on page 20-21).

Cambisol Soil in an early stage of development.

Carbonate rocks A rock consisting of chiefly of carbonate minerals, such as limestone and dolomite.

Casing A solid piece of pipe, typically steel or PVC plastic, used to keep a well open in either unconsolidated materials or unstable rock.

Cementing The operation by which grout is placed between casing and the sides of the well bore to a predetermined height above the bottom of the well. This secures the casing in place and excludes water and other fluids from the well bore.

Cone of depression A depression in the groundwater table or the potensiometric surface that has the shape of an inverted cone and develops around a well from which water is withdrawn. It defines the area of influence of a well.

Conglomerate A sedimentary rock containing rounded water-worn fragments of rock or pebbles, cemented together by another mineral substance.

Cl Chloride.

Contaminant Any solute or cause of change in physical properties that renders water unfit for a given use.

CO_2 Carbon dioxide.

CSIR The Council for Scientific and Industrial Research, Republic of South Africa.

Cu Copper.

d Day.

D Water saturated thickness in metre.

Darcy's Law A derived equation for the flow of fluids on the assumption that flow is laminar and that inertia can be neglected.

Desalination To remove salt and other chemicals form sea or saline water.

Discharge area An area in which there are upward components of hydraulic head in the aquifer - Groundwater is flowing toward the surface in a discharge area and may escape as a spring, seep, or baseflow or by evaporation and transpiration.

Drainage basin The land area form which surface runoff drains into a river system.

Dolerite A coarser grained rock of basaltic composition intruding as dykes or sills within the earth's crust.

Dolocrete Gravel, sand or desert debris cemented by porous calcium magnesium carbonate.

Drawdown The lowering of the water table of unconfined aquifer or the potensiometric surface of a confined aquifer caused by pumping of groundwater from boreholes.

Dunite A nonfeldspathic plutonic rock consisting almost entirely of olivine and containing accessory pyroxene and chromite.

Durisol Hard crust soil.

DWA Department of Water Affairs, Windhoek, Namibia.

DPA Discontinuous Perched Aquifer.

E East.

EEC European Economic Commission, Brussels, Belgium.

EC Electrical conductivity of water in µS/cm or mS/cm at 25 ° C.

Effluent A waste liquid discharge from a manufacturing or treatment process, in its natural state or partially or completely treated, that discharges into the environment.

e.g. For example.

Electrical conductance A measure of the ease with which a conducting current can be caused to flow through a material under the influence of an applied electric field. It is reciprocal of resistively and is measured in mhos metre.

Electrical resistively The property of a material which resists the flow of an electric current measured per unit length through a unit cross sectional area.

ENWC Eastern National Water Carrier (see Box on page 70-71).

Equipotential line A contour line on the water table or the potensiometric surface, a line along which the pressure head of groundwater in an aquifer is the same. Fluid flow is normal to these lines in the direction of decreasing fluid potential.

Evaporation The process by which water passes from liquid to vapour state.

Evapotranspiration Loss of water from a land area through transpiration of plants and evaporation form the soil.

Facies A stratigraphic body as distinguished from other bodies of different appearance and composition.

Fault A fracture or a zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.

Fe Iron.

Ferralsol Soil with a high content of iron oxides.

Filterpack Sand or gravel that is smooth, uniform, clean, well-rounded and siliceous. It is placed in the annulus of the well between the borehole wall and the well screen to prevent formation material from entering the screen.

Floodplain The surface or strip of a relative smooth land adjacent to a river channel, constructed by the present river and covered with water when the river overflows its banks. It is build of alluvium carried by the river during floods and deposited in the sluggish water beyond the influence of the swiftest current.

fluvial, fluviatile Pertinent to the action of river water.

Fm Formation.

Fossil water Interstitial water that was buried the same time as the sediment.

Foyaite Syenitic rocks containing almost equal proportions o feldspathoids and potash feldspars.

fresh <1 000 mg/L TDS or <150 mS/m EC or Group A quality.

Gabbro Dark-coloured, basic intrusive rock.

GKA Grootfontein Karst Aquifer comprising synclines 1 to 3.

Gleysol Excessively wet soil with a gley horizon.

GOC Grootfontein-Omatako Canal.

Granite Quartz-bearing, plutonic rock.

Groundwater The water contained in interconnected pores located below the water table in an unconfined aquifer or located in a confined aquifer.

Groundwater basin A rather vague designation pertaining to a groundwater reservoir that is more or less separated from neighbouring groundwater reservoirs. A groundwater basin could be separated from adjacent basins by geological boundaries or by hydrological boundaries.

Groundwater flow The movement of water through openings in sediment and rock; occurs in the zone of saturation.

Groundwater table The surface between the zone of saturation and the zone of aeration; the surface of an unconfined aquifer.

Group A No risk, excellent water quality.

Group B Insignificant risk, good quality water.

Group C Low risk.

Group D High risk or water unsuitable for human consumption.

GSN Geological Survey of Namibia, Windhoek.

ha Hectare, (1 ha = 10 000 m^2).

Hardness A property of the water causing formation of an insoluble residue when water is used with soap. Sum of the ions which can precipitate as “hard particles” from water. Sum of Ca^{2+} and Mg^{2+}, and sometimes Fe^{2+}. Expressed in mg/L $CaCO_3$ or in hardness degrees. Temporary hardness is the part of Ca^{2+} and Mg^{2+} concentrations, which are balanced by HCO_3^- and can thus precipitate as carbonate. Permanent hardness is the part of Ca^{2+} and Mg^{2+} being in excess HCO_3^-. Total hardness is the sum of temporary and permanent hardness.

Hardness ranges [mg/L $CaCO_3$] (0 - 75 = soft; 75 - 150 = moderately hard; 150 - 300 = hard; > 300 = very hard).

HCO_3 Bicarbonate.

Head Energy contained in a water mass, produced by elevation, pressure, or velocity.

heterogeneous Pertaining to a substance having different characteristics in different locations. A synonym for non-uniform.

homogeneous Pertaining to a substance having identical characteristics everywhere. A synonym is uniform.

Hydraulic conductivity A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining the hydraulic conductivity.

Hydraulic gradient The change in the total head with the change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.

Hydraulic parameter Values (K, T, s) that are determined quantitatively to characterise the aquifer, and are used for modelling.

Hydrogeology The study of interrelationships of geologic materials and processes with water, especially groundwater.

Hydrologic cycle The circulation of water from oceans through the atmosphere to the land and ultimately back to the ocean.

Hydrology The study of the occurrence, distribution and chemistry of all waters of the earth.

IAEA International Atomic Energy Agency.

i.e. That is.

Igneous rocks Rocks that solidified from molten material, that is, a magma.

Inselberg Erosion rest of previously wider extended rock cover.

Intrusive rocks Those igneous rocks that formed from magma injected beneath the earth’s surface. Generally these rocks have large crystals by slow cooling.

Ion exchange A process by which an ion in a mineral lattice is replaced by another ion that was present in aqueous solution.

isostatic Subject to equal pressure from every side; being in hydrostatic equilibrium.

Isopach Contour lines indicating areas of equal depth.

K Hydraulic conductivity in m/d or m/s, K = T/D.

Karst The type of geologic terrain underlain by carbonate rocks where significant solution of the rock has occurred due to the flowing of groundwater.

km Kilometre.

L Litre.

Landfill A general term indicating a disposal site of refuse, dirt from excavations, and junk.

lacustrine In a lake environment.

Leachate A liquid that has percolated through solid waste and dissolved soluble components.

Leptosol Shallow, stony soil overlying rock.

Limestone A sedimentary rock consisting chiefly of calcium carbonate, primarily in the from of the mineral calcite.

Lithology, lithologic Rock composition, rock type.

Luvisol Soil with prominent illuvial accumulation of clay in the subsoil.

m Metre.

m^2 Square metre.

Ma Million years.

MAC Maximum Admissible Concentration.

Mantle Layer of the earth between crust and core.

MDA Main Deep Aquifer.

Mm^3 Million cubic metre.

Mm^3/a Million cubic metre per annum.

meteoric Pertaining to recent atmospheric water.

Metamorphic rocks Any rock derived from pre-existing rocks by mineralogical, chemical, and /or structural changes, essentially in a solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment, generally at depth in the Earth’s crust.

Mg Magnesium.

Mg/L Milligrams per litre of sample.

Min Minute.

mm Millimetre, e.g. 10 mm rainfall equals 10 L/m^2.

mS/m MilliSiemens /metre, dimension of EC, =10 µS/cm.

N North.

Na Sodium.

n/a Not applicable, not available.

NamWater Namibia Water Corporation (Ltd.), Windhoek.

NO^3 Nitrate.

OAA Oshivelo Artesian Aquifer.

Observation well A well drilled at a selected location for the purpose of observing parameters such as water levels and pressure changes.

ODA Otavi Dolomite Aquifer.

Ol Olukondo formation.

OMAP Omaruru River alluvial plain.

OMDEL Omaruru River Delta (see Box on page 83).

OMPL Ongopolo.

Orogeny The process of forming mountains, particularly by folding and thrusting.

Pb Lead.

pedogenic Related to soils or soil water.

Pelite Fine grained, clayey sediment.

Permeability The property or capacity of a porous rock, sediment, or soil transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure.

petrographic Concerning the mineralogical composition of rocks.

pH A measure of the acidity and alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with increasing alkalinity and decreasing with increasing acidity. Originally stood for the words potential of hydrogen. It is calculated as -log [H$^+$], the log of H$^+$ activity.

Phyllite A metamorphosed clay-bearing rock intermediate in grade between slate and schist.

piezometric head Pressure head of groundwater in a well or borehole.

plutonic rock An igneous rock formed when magma cools and crystallises within the earth.

Pollutant Any solute or cause of change in physical properties that renders water unfit for a given use.

Pore space The volume between mineral grains of a porous medium.

Porosity The ration of volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

potentiometric surface A surface that represents the level o which water will rise in tightly cased boreholes. If the head varies significantly with the depth in the aquifer, then there are may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer.

Primary porosity The porosity that represents the original pore openings when a rock or sediment is formed.

Pumping test A test made by pumping a borehole for a period of time and observing the change in the hydraulic head of the aquifer. A pumping test may be used to determine the capacity of the borehole and the hydraulic characteristics of the aquifer. Also called an aquifer test.

Pyroclastics A rock consisting of unreworked solid material of whatever size explosively or aerially ejected from a volcanic vent.

Pyroxenite A medium or coarse-grained rock consisting essentially of pyroxene.

Q Pump discharge in m^3/h.

Quartzite A granulose metamorphic rock consisting essentially of quartz granules.

Recharge The addition of water to a zone of saturation; also, the amount of water added.

Recharge area An area where there are downward components of hydraulic head in the aquifer. Infiltration moves downward into the deeper parts of an aquifer in the recharge area.

Recharge basin A basin or pit excavated to provide means of allowing water to soak into the ground at rates exceeding those that would occur naturally.

Recharge well A borehole specifically designed so that water can be pumped into an aquifer in order to recharge the groundwater reservoir.

Recovery The rate at which the water level in a well rises after the pump has been shut off. It is the inverse of draw down.

Regosol Soil with weak or no development.

Rhyolite An extrusive equivalent of a granite.

River, ephemeral A river that is mostly dry and only subject to water flow for short periods after heavier rainfall events.

River, perennial A river that is subject to flow throughout the year.

Runoff The total amount of water flowing in a stream. It includes overland flow, return flow, interflow and baseflow.

s Second.

s Storage coefficient.

S South.

Safe yield The amount of naturally occurring groundwater that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native groundwater quality or creating an undesirable effect such as environment damage. It cannot exceed the increase or leakage from adjacent strata plus the reduction in discharge, in which due to the decline in head caused by pumping.

Saline >10 000 mg/L TDS or >1500 mS/m EC or Group D quality.

Salinity ranges Classification: TDS [mg/L] / EC [mS/m] (fresh = < 1000 / <150; brackish = 1000 to 10 000 / 150 to 1500; saline = >10 000 / >1500).

Sandstone A sedimentary rock composed of abundant rounded or angular fragments of sand set in a fine grained matrix (silt or clay) and more or less firmly united by cementing material.

Sapropelite A fluid organic slime originating in swamps as a product of putrefaction. Often contains hydrocarbons. Substance becomes tough when dry.

saturated zone The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.

Schist A medium or coarse-grained metamorphic rock with sub-parallel orientation of the micaceous minerals which dominate its composition.

secondary porosity The porosity that has been caused by fractures or weathering in a rock or sediment after it has been formed.

sedimentary rock A rock formed from sediments through a process known as diagenesis or formed by the chemical precipitation of water.

Shale A fine-grained sedimentary rock, formed by the consolidation of clay, silt and mud. It is characterised by finely laminated structure and it is sufficiently indurated so that it will not fall apart on wetting.

Siltstone A very fine-grained consolidated clastic rock composed predominantly of particles of silt grade.

SO_4 Sulphate.

Solonetz Soil with B horizon rich in sodium and/or magnesium.

Solonchak Soil having a high salinity and no well-developed subsurface horizons.

static water level The level of water is a well that is not being affected by withdrawal of water.

Storativity, storage coefficient The volume of water an aquifer releases from or takes into storage per unit surface area of an aquifer per unit change in hydraulic head. It is equal to the product of specific storage and the aquifer thickness. In an unconfined aquifer the storativity is equivalent to the specific yield. Also called storage coefficient.

Stratigraphy A study of rock strata, especially in their distribution, deposition and age.

Surface water Water found in ponds, lakes, inland seas, streams and rivers.

Syenite A plutonic igneous rock consisting principally of alkalic feldspar usually with one or more mafic minerals such as hornblende or biotite.

T Temperature in °C.

T Transmissivity.

TCL Tsumeb Corporation Ltd. (Member of Gold Fields Namibia Ltd.).

TDS Total dissolved solids in mg/L; (sum of cations and anions); (in DWA analytical reports TDS is calculated: TDS = 6.6 x EC).

TKA Tsumeb Karst Aquifer comprising the Abenab-Tsumeb Synklinorium.

TH Total hardness, refer to “Hardness”.

Transmissivity The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of the properties of the liquid, the porous media and the thickness of the porous media.

Transpiration The process by which water absorbed by plants, usually through the roots, is evaporated into the atmosphere form the plant surface.

Travertine Calcium carbonate, of light colour and usually concretionary and compact, deposited from solution in ground and surface waters.

Tufa A chemical sedimentary rock composed of calcium carbonate or of silica, deposited from solution in the water of a spring or lake or from percolating ground water.

UKA Unconfined Kalahari Aquifer.

US-EPA United States Environmental Protection Agency, Washington, D.C.

V Vanadium.

VDA Very Deep Aquifer.

Vertisol Soil topped with clay which crack when dry.

Vlei A small swamp, usually open and containing a pond.

Volcanic rock An igneous rock formed when molten rock called lava cools on the earth’s surface.

W West.

Water budget An evaluation of all the sources of supply and the corresponding discharges with respect to an aquifer or drainage basin.

Water table The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric. It can be measured by installing shallow wells extending a few metres into the zone of saturation and then measuring the water level in those wells.

Water type Ions with a relative concentration (fraction) ≥ 20 meq % are name-giving, e.g. Ca-Mg-HCO_3.

Well screen Filtering device used to keep sediment from entering well.

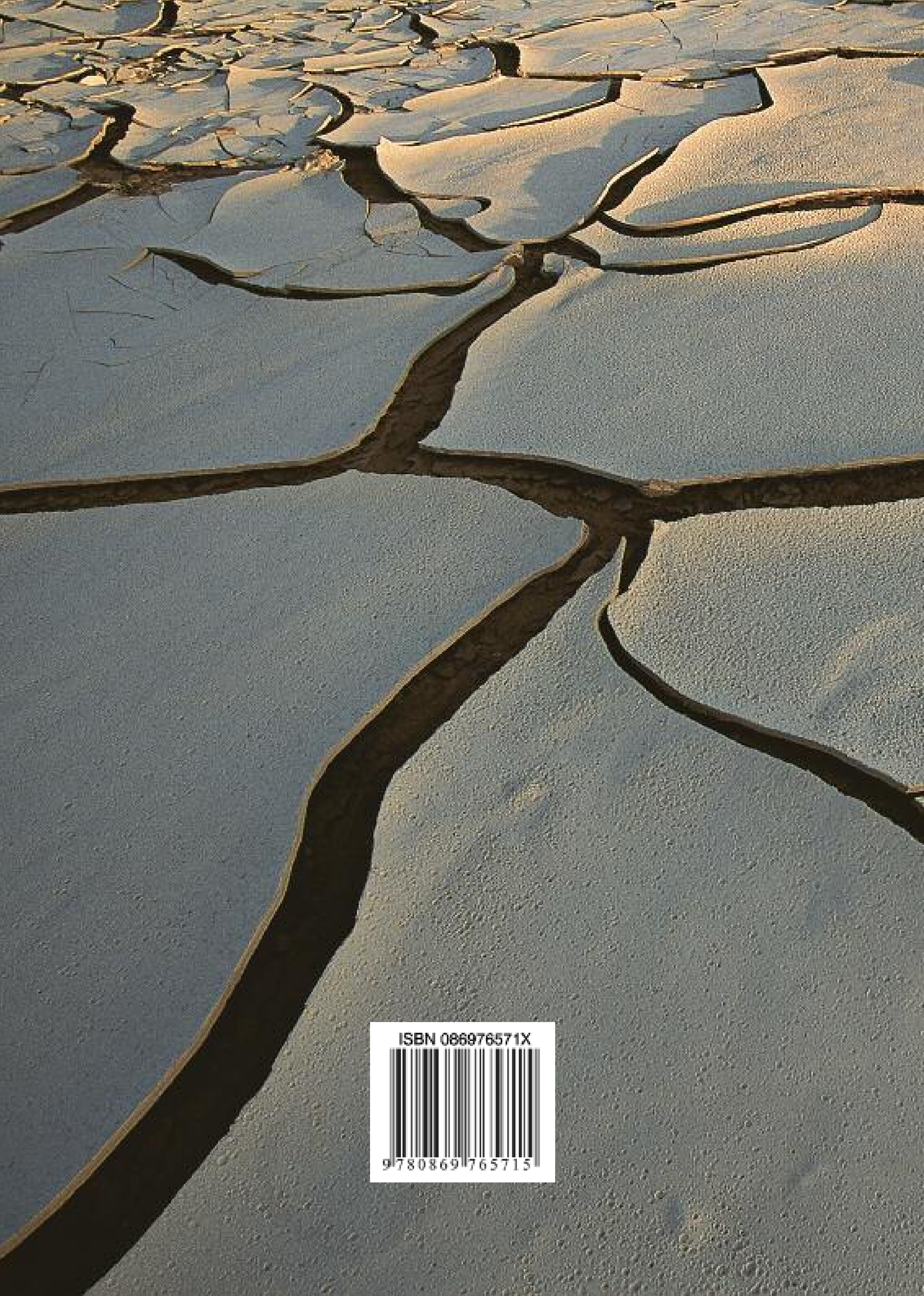
Well yield The volume of water discharged from a well in cubic metres per hour or cubic metres per day.

Weir A device placed across a stream and used to measure the discharge by having water flow over a specifically designed spillway.

WHO World Health Organisation, Geneva, Switzerland.

WL Water level in metres below ground level (bgl).

Zn Zinc.



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