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,

Mukorob shale, between Nossob and Auob

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

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.

Jürgen Kirchner

Longitudinal dunes after heavy rains

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.

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.

Jürgen Kirchner

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.

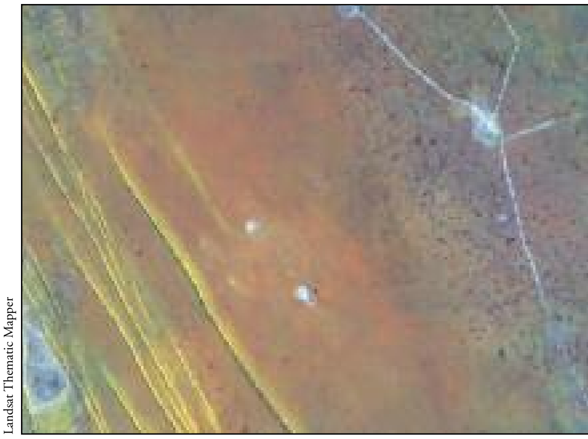
Wilhelm Struckmeier

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.
	Schwarz-rand	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

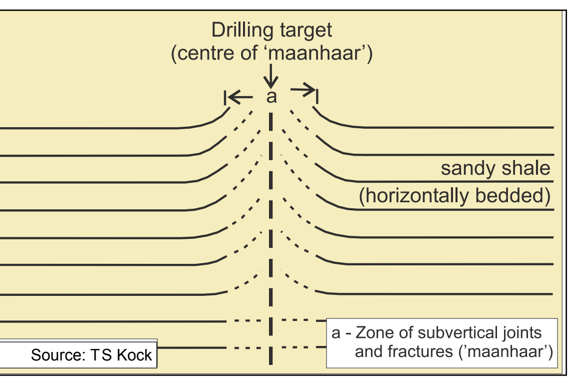
North-striking east-dipping fault, sandstone, Nababis Formation. Farm Aneis, along District road No 1075

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

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.



"Maanhaar" features may indicate good drill sites

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.

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.

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.

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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

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

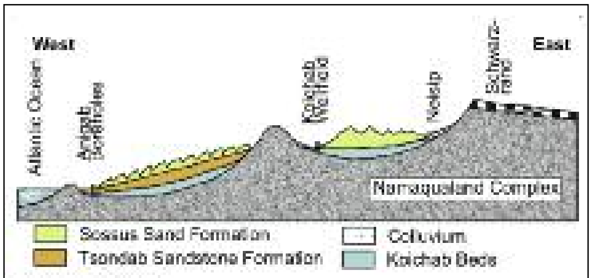
The carbonate rocks of the Naukluft are heavily karstified. Numerous springs and waterfalls are fed by this huge karst groundwater body which may be described as a natural lysimeter discharging above the low permeable sediments of the Nama Sequence. Also tufa or travertine formations are typical for 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

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).



Source: S Müller

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

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.

Kevin Roberts

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 2000 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,

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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).

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.

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.

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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".

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.

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.

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