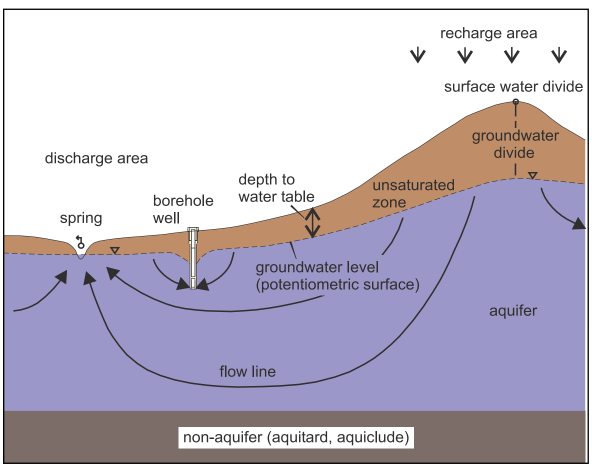
Essentials of Groundwater

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

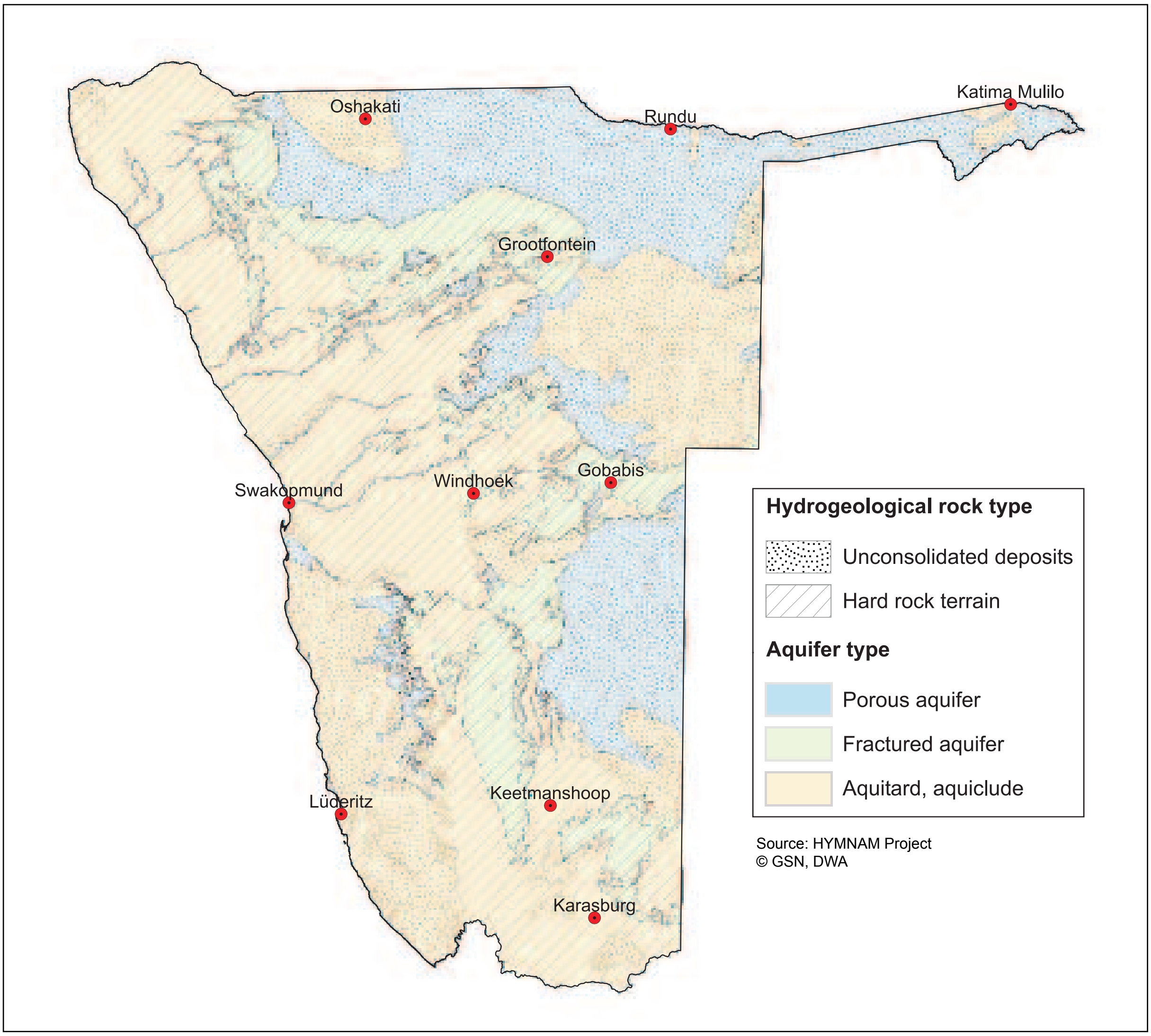
The potential of an aquifer to yield a certain quantity of water with a certain chemical quality at a certain rate depends on its size, the volume of water that can be stored, (called the storage capacity) the chemical composition of the rocks that the water comes into contact with, the volume of water 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



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.

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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.

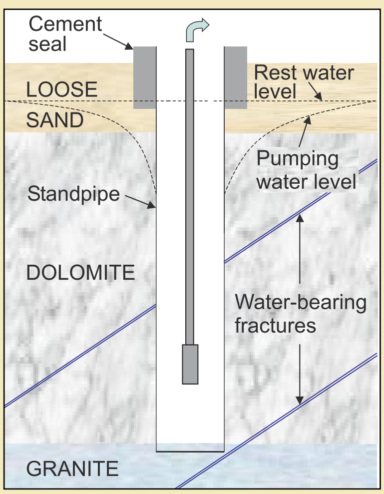
In a semi-arid to arid country like Namibia, it is of crucial importance that groundwater abstraction volumes are known

Borehole design

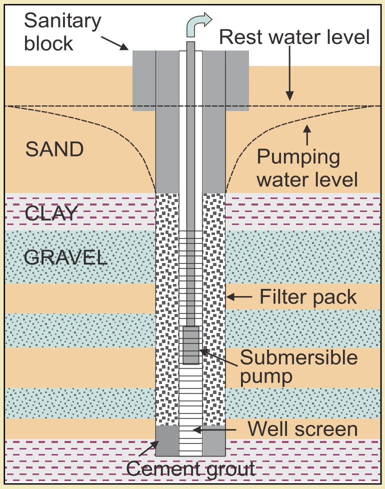
A borehole is a hydraulic structure that permits the abstraction of water from an underground water bearing formation. Since boreholes are drilled into the ground and some of the equipment to abstract the groundwater is located underground, the capital investment in the installation is only partially 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.

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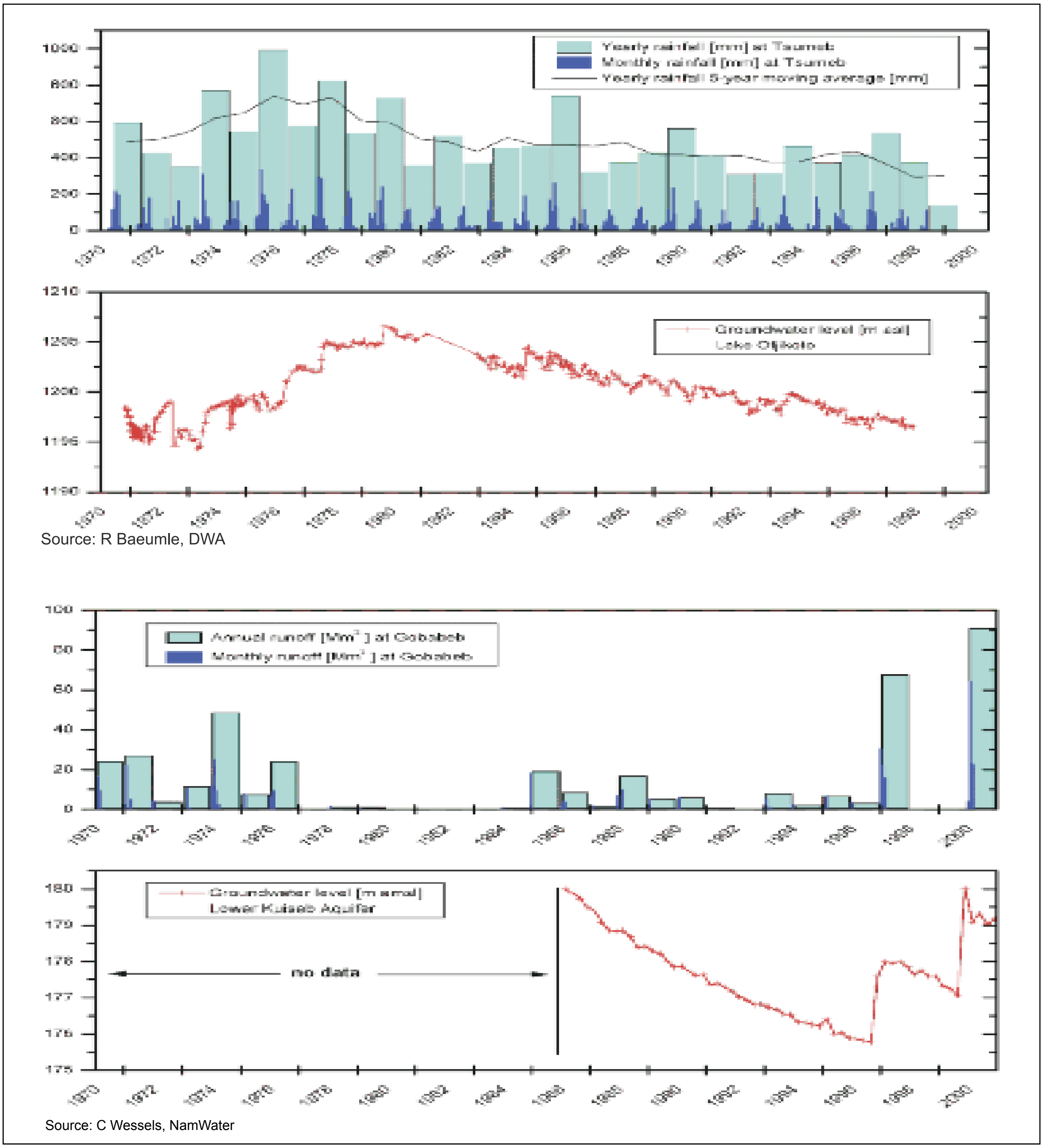
Jürgen Kirchner

African IAEA training course at artesian borehole in Stampriet



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

Tsumeb open dumping sites

Sindila Mwiya

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

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.

Landsat Thematic Mapper Image

Gobabis open dumping site

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.

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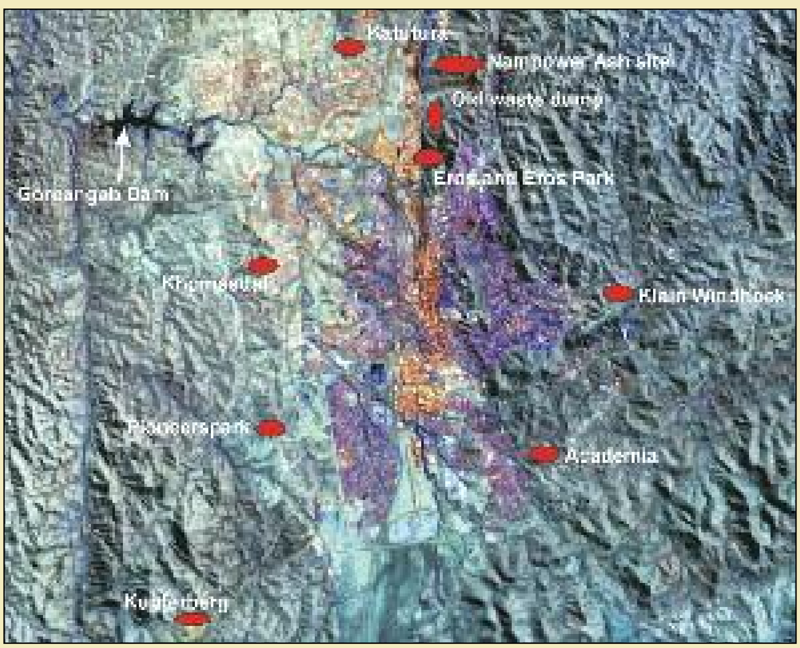

Landsat Thematic Mapper (TM) band 1, 2 and 4 (false colour composite)

Windhoek's waste disposal sites